The influence of perceived temperature on human well-being in the context of climate change

A multi-level global analysis

Dissertation

zur Erlangung des Doktorgrades

der Naturwissenschaften (Dr. rer. nat)

am Fachbereich Geographie (FB 19)

der Philipps-Universität Marburg

vorgelegt von:

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To

those who follow, that they may

stand higher, see more clearly, reach further, and grasp

more than we. May they have the wisdom to help others to do the same.

Abstract

Anthropogenic climate change is causing global shifts in climate. Mean global temperatures are increasing extremely rapidly. One direct consequence of this is that in many places perceived temperature is higher than before. This is due to shifts in both temperature and humidity as the climate system reacts to the higher level of heat and the accompanying processes redistributing warm air and moisture in the atmosphere.

Hot weather has been shown to be potentially dangerous in many contexts to various aspects of human life. From a health perspective, heat creates additional stress for the body, potentially impacting the circulatory and nervous systems. Exhaustion rates increase and the need for hydration rises.

Beyond the direct effects on health, heat can also affect other human systems, either directly or indirectly through ancillary mechanisms. Exhausted workers are less productive. Sickness and mortality creates costs for economies and slows economic growth. Heat also affects the temperature of coolant water for power plants, the growth rates of plants, and many other components of economies that are connected with human well-being.

In this thesis I discuss the increase in perceived temperature over the past three decades. I examine its effects on mortality in Europe and on economic growth rates worldwide. The findings indicate that perceived temperature is increasing for most of the world, and that higher mortality rates can be expected as a result. Additionally, economic growth can be expected to slow in the presence of longer and more frequent heat waves.

Zusammenfassung

Der anthropogener Klimawandel verursacht globale Veränderungen im Wetter. Eine direkte Folge sind gefühlte Temperaturen, die vielerorts höher sind, als in Vergangenheit beobachtet wurde. Das Klimasystem reagiert auf die zusätzliche Wärme durch eine Umverteilung warmer Luft und Feuchte in der Atmosphäre, was zu Veränderungen in der globalen Verteilung von Humidität und Temperatur führt.

Heißes Wetter birgt Gefahren für verschiedene Aspekte menschlichen Lebens. Medizinisch betrachtet, verursachen hohe Temperaturen Stressreaktionen im Körper, die Auswirkungen auf das Nervensystem und den Blutkreislauf haben. Auch steigen mit der Temperatur die Ermüdungsrate und der Bedarf an Wasser.

Über die direkten Auswirkungen auf Gesundheit hinaus nimmt Hitze auf verschiedene Weise - sowohl direkt als auch indirekt - auf menschliche Systeme Einfluss. Ermüdete Arbeitskräfte sind weniger produktiv. Krankheit und Mortalität verursachen Kosten für Wirtschaften und bremsen Wirtschaftswachstum. Ebenso beeinflusst Hitze die Temperatur von Kühlwasser für Kraftwerke, die Wachstumsrate von Pflanzen und viele andere Komponenten von Wirtschaften, die mit dem Wohlergeben des Menschen zusammenhängen.

In dieser Dissertation untersuche ich die Zunahme gefühlter Temperatur in den letzten drei Jahrzehnten und die Auswirkungen dieser Zunahme auf Mortalität in Europa und globale Wirtschaftswachstumsraten. Die Ergebnisse zeigen, dass gefühlte Temperatur fast überall auf der Welt zunimmt, und dass folglich höhere Sterblichkeitsraten zu erwarten sind. Darüber hinaus ist davon auszugehen, dass Wirtschaftswachstum durch längere und häufiger vorkommende Hitzewellen gebremst wird.

Contents

Chapter 1

Introduction

The gravity of the situation

Climate change is one of the greatest challenges mankind has ever faced. After having experienced several centuries of relatively stable climatic conditions worldwide, long-term weather patterns are shifting across the entire planet [IPCC, 2014a].

Climate change is not unprecedented, and in fact the climatological stability we have enjoyed over the past few centuries is more the exception than the rule [Bond et al., 1997]. The earth's mean temperature has varied greatly throughout its history. The last glacial maximum is an especially notable contrast to current climate conditions in the Earth's recent history, and likely have played a crucial role in our development as a species [Carto et al., 2009]. This time, in which glaciers covered much of the Earth's surface, is so recent that many ecosystems and landscapes are still in the process of transitioning from that climate to our current one [Peltier, 2004].

Our planet's history since then has also been far from static, but the speed and scope at which the climate has changed since then can hardly be compared to that of the current transition we find ourselves in [Diffenbaugh and Field, 2013]. Since industrialization swept the Western world and revolutionized human economies and cultures worldwide, Earth's natural systems across the planet have been pushed to absorb higher amounts of heat. This caused them to transition to a new climate with unprecedented speed [Canadell et al., 2007, Solomon et al., 2009]. It is indisputable that humans are the driving force behind this process. Our willingness and ability to mitigate our influence on the climate will play a large part in determining the richness and complexity of our planet's ecosystems in the future.

Despite the gravity of this challenge, climate change at a slower pace is not an unfamiliar face in human history. Past shifts in climate likely played a large role in initiating mankind's colonization of most of the planet [Stewart and Stringer, 2012]. Shifting climates have brought fortune or fall to many of our species' greatest empires: the Mayas in Central America [Kennett et al., 2012]; the Anasazi in North America [Benson et al., 2007]; the Romans in Europe [Büntgen et al., 2011] and the Mongolians in Asia [Pederson et al., 2014], to name but a few. Like our own, the fates of these great civilizations were intimately intertwined with the long-term weather patterns influencing their lives and the lives of the societies around them.

Modern society has changed in many ways, so that modern life would likely seem as foreign and incomprehensible to the inhabitants of any of the previously named societies as life in Rome would have seemed to an ancient Mayan. Our cultures and economies are interconnected with each other, and through technology, many natural forces which previously decided over life and death are hardly noteworthy in day-to-day life. Yet among the many differences separating us from our progenitors, much has stayed the same. Among them is the fact that our ability - or inability - to adapt successfully to our changing environment will determine if we can preserve our way of life. This time, however, the environment in question is not restricted to a region, but to our planet, and it is not the fate of our society, but our species, which is at stake [IPCC, 2014a].

The scope of these issues extends far beyond that of a single thesis, and in fact the focus of this work is microscopic in comparison. Instead, we will devote the following pages to a small aspect of climate change: The direct effects of increased heat load on humans and human well-being. The focus will lie on the results of direct interactions between humans and their environment, rather than on the indirect effects of the changing climate on the distribution of resources and the resulting advantages and disadvantages for humans.

I show that heat has had significant influence on humans in the recent past and that we can expect these effects to be stronger in the future. Particularly, I focus on two factors: Economic growth and death rates. Death rates are relevant to human well-being in a straightforward fashion - death robs individuals of their life and loved ones, subtracts cultural and technical knowledge from communities and reallocates valuable resources within economies. Economic growth, on the other hand, may seem more trivial to human well-being from a long-term perspective. However, economic well-being, which is often the result of economic growth, enables humans to pursue more abstract values than when they are forced to focus on subsistence. Civil liberties, cultural development and the emergence of the technologies necessary to fight climate change and improve quality of life all are contingent upon it [Helliwell, 1994]. Therefore economic growth plays an important role as a driver of the more worthy goals of human rights, environmental protection and cultural advancement.

Key concepts and assumptions

The key concepts of this thesis are climate change, the additional heat load it imposes on humans, and human quality of life. All three of these topics are large enough to fill multiple doctoral theses and indeed, each is the exclusive topic of many larger works. This thesis attempts to consolidate these concepts and examine the point at which they intercept.

Climate change and human economies: Two interconnected systems

The Earth's climate is only constant in the sense that it is constantly changing. For the purpose of the following chapters, however, these natural climate fluctuations are not the issue. The topic of discussion is anthropogenic climate change.

Anthropogenic climate change is a complex process which has taken place on various scales throughout human existence [Büntgen et al., 2011]. This began most notably with agriculture [Salinger, 2007]. The change in land use on a wide scale from forest to farmland exerted very tangible influences on the biosphere. Furthermore, changes to regional water and energy households - changes in the land albedo by crop planting, for example, or water flow diversion for irrigation purposes - has long been able to influence mean temperature and humidity in the direct vicinity [Qian et al., 2013]. If this takes place on a large enough scale, air circulation patterns can change as well. The interconnectedness of land albedo, water retention rates, heat and precipitation are easily visible in the modern example of urban heat islands. This phenomenon is well-documented: Cities have different climates than the surrounding land. They have lower water retention rates and thus lack water as a heat sink [Mitchell et al., 2001]. This leads to higher diurnal temperature fluctuations. Additionally, low albedo cityscapes reflect less energy out into space, instead retaining it in the form of heat [KIM, 1992]. Finally, the heat rising from cities - combined with a high aerosol content in the air - provides both the convection and the condensation cores needed to support higher precipitation downwind [van den Heever and Cotton, 2007].

Some argue that changes in land use - particularly through clearing forests and replacing them with farming or grazing land - has the potential to change large-scale circulation patterns and may have done so in the past [Cui et al., 2006]. More crucially, perhaps, the reduction of ecosystem complexity that accompanies the replacement of forests by fields releases carbon dioxide and other climate gases into the atmosphere, while simultaneously lowering the land surface's capacity to capture and store carbon [West and Marland, 2002, Post and Kwon, 2000a].

The anthropogenic influence of the global carbon cycle is the crucial mechanism by which mankind has changed and continues to change the climate on a global scale [IPCC, 2014b]. Since the beginning of the industrial revolution, mankind has accelerated the introduction of carbon to the atmosphere by burning hydrocarbons in order to access the energy locked in their chemical bonds [Canadell et al., 2007]. This is energy originally captured from light produced by the sun and converted to chemically stored potential energy. If the plant matter thus produced through photosynthesis are subject to special conditions, they can transition to extremely stable bonds which can fossilize and retain the energy they store for extreme periods of time. Hydrocarbons, for example coal, oil and natural gas, can hold energy almost indefinitely [Tissot and Welte, 1978].

Throughout the history of life on our planet, energy stored in this form has accumulated to massive stores. Humans have a long history of exploiting them in order to access their energy. For example, coal has long been a source of energy for heat, which can either be used directly or converted by various means to other forms of energy [Théry et al., 1996]. The past century has seen great technological advances as a result of this, which have in turn led to the ability to use hydrocarbons more efficiently, as well as access stores which had previously been inaccessible [Berndt, 1990]. The energy thus gained can be used to support economic growth and increase consumption - a cycle that spirals toward ever higher carbon emission rates.

The energy stored in these hydrocarbons is negligible when weighed against the Earth's energy budget [Rogner, 1997, Trenberth et al., 2009]. However, their combustion results in the emission of carbon into the atmosphere in the form of climate gases, which change the atmosphere's ability to retain thermal energy. Carbon dioxide is the most notable among these climate gases due to its long persistence in the atmosphere. Thus by burning hydrocarbons, humans change the atmosphere's composition so that it retains heat from the Sun better. Because the diffusion of solar energy into space is slowed, the Earth's thermal equilibrium point is raised and thus mean temperatures rise globally [IPCC, 2014b].

The results are complex. For example, changes in the distribution of heat in the atmosphere affect global circulation patterns, which in turn change temperatures and precipitation rates worldwide. The effects are felt in ecosystems, glaciers and in ocean circulation, to name but a few, all of which in turn influence each other and play a role in the planet's ability to diffuse heat into space [van Ulden and van Oldenborgh, 2006].

The most direct effects of climate change are felt through higher temperatures, and in the changed circulation patterns that this causes in the atmosphere. This in turn affects a number of other weather variables, notably precipitation, which has already been observed to change significantly in many regions (e.g. California and Norway, to name a few) [Williams et al., 2015, Hongve et al., 2004].

The concentration of carbon dioxide in the atmosphere is the main driving force behind these mechanisms. Since mankind began burning large amounts of hydrocarbons in earnest, the concentration of this climate gas in the atmosphere has increased significantly. Because the modern way of life which many humans have become accustomed to requires a high rate of energy consumption, it can be expected that hydrocarbon consumption in order to gain access to energy will not slow quickly. An abrupt cessation of the use of fossil fuels would effectively end modern society as we know it. Thus we can expect the concentration of carbon dioxide, with all of its side effects, will increase in the future [IPCC, 2014a].

Yet even if mankind were to abruptly cease carbon emissions, the changes that we have introduced to our planet would still take centuries to unfold [Eby et al., 2009]. We are at the beginning of a long transition to a new climate of our making, and while we can, within limits, steer the train and brace for impact, it has nonetheless left the station and there is no calling it back.

Heat: A key component in human well-being

The root cause of anthropogenic climate change is heat retention in the atmosphere. This makes it clear that heat is an essential component in climate change. However, as humans are the centerpiece of the work introduced here, this thesis' perspective on heat will be nuanced beyond the basic definition of heat as a measure of mean kinetic energy.

When examining the direct influence of higher heat loads on humans, we are discussing the physiological load exerted by heat on human bodies. The human energy household is dependent on many internal factors and thus the transfer of heat into and out from human bodies is a complex process involving many mechanisms and factors both inside and outside the body.

Humans are endotherms, and thus maintain a high level of metabolic activity, resulting in heat production from within the body. Additionally, the body can receive heat from its surroundings through radiative heating - such as when the sun shines on a person's skin - and through contact with materials that have a higher temperature

[Benzinger, 1969]. Most often the material in question is air.

Heat leaves the body, as it does any object, through radiation, as well as through conduction. Thus the body warms its environment. If the body is surrounded by a fluid, such as air, the rate of heat transfer can be increased through convection. Also, heat can leave the body in the form of latent warmth via the evaporation of liquids. In fact, the heat transfer through evaporation is such a powerful mechanism that humans have evolved extensive biological mechanisms to aid thermoregulation by producing sweat. Sweat carries away large amounts of thermal energy when it evaporates and is thus an important thermoregulatory vehicle for humans [Kenny and Journeay, 2010].

The convergence of these heat transfer mechanisms produces a number of ancillary possibilities to regulate heat transfer through behavior, so that additional factors must be considered when discussing the regulation of the temperature of a human body. These include purposefully moistening skin in order to lower its temperature through conduction or to increase evaporation rates and thus the loss of latent heat. They also include moving into the shade, thus slowing the rate of radiative energy input by reducing the amount of radiation absorbed. Also, exposing skin to wind increases the speed of both evaporation and conductive heat transfer [Newburgh, 1968].

Such behavioral regulatory measures are also adopted by other animals with similar biological adaptations (most notable among these are equines, whose sweat is most comparable to that of humans) [Hodgson et al., 1994]. Humans, however, employ additional, novel methods of modifying the rate of heat transfer between their bodies and the environment or decreasing heat load by modifying the temperature of their immediate environment.

One simple mechanism is through the use of buildings. Not only do buildings provide shade, thus limiting the rate of radiative uptake, they also provide shelter from the wind. This can have ambiguous effects on temperature inside a building, dependent on ventilation and building materials. For example, a building with large glass windows can absorb heat in the form of radiative transfer from sunlight. This heat is then transferred from the absorbing material to the surrounding air. In an open environment, the air would fairly quickly be moved out of the enclosure, taking the absorbed heat with it. However, in an unventilated building, the air and thus the heat can become trapped, so that the air in the building has a higher temperature than the ambient air outside [Eicker, 2010].

This is simply the tip of the iceberg of the complexity of heat transfer within buildings. This complexity is compounded by cultural differences in bulding usage, as well as access to materials and technologies. The frequency and duration of building ventilation is dependent upon local preferences, current weather conditions, building style and culture. The use of auxiliary temperature regulation technologies, such as air conditioning or heaters, is also contingent on the same factors, as well as access to the resources needed to utilize them [Schweiker and Shukuya, 2009].

Clothing is another important factor. Some styles of clothing shield the body from radiative heat, thus lowering heat intake rates. Simultaneously, clothing can decrease the rate of the body's heat loss by trapping air close to the body. This prevents heat from escaping the body through convection and can also limit the efficiency of heat loss through evaporation, because the air becomes saturated with moisture from the body [Hajat et al., 2010].

Other important behavioral factors include diet and physical activity levels [Solecki et al., 2005]. Heavy foods divert the body's resources for digestion, which also raises the body's heat production level [Moneta et al., 1988]. Physical activity in general also increases heat production [Bakkevig and Nielsen, 1995].

The cumulative effect of these facts is that it is exceedingly difficult to quantify heat load on the human body in any meaningful way. Within a region, fluctuations in air temperature and moisture change the rate of heat dispersion from a body into the air. Irradiation can vary widely depending on topography and land use. Urban environments, where wind, irradiation and ventilation of buildings can cause wide fluctuations of the variables mentioned above on a small spatiotemporal scale, present even larger difficulties when attempting to forecast the physiological heat load on humans. Furthermore, even if all these factors were known, the individual level of activity, clothing, diet and general disposition toward hot weather would be unknown.

Nonetheless, many studies do attempt to quantify the effects of heat on humans (including the present thesis). The conclusions that can be drawn from these studies is largely dependent on understanding the capabilities and limitations of the given study, which are mostly dependent on the available data and the spatiotemporal scale. Highly accurate metrics which take into account a subject's clothing, weight, volume, etc. are of value when examining the mechanisms with which the human body disperses heat and the effects of heat on humans [e.g., Fiala et al., 1999, Konz et al., 1977]. However, these cannot be extrapolated onto a group of individuals in a straightforward fashion. Other metrics aim to quantify the heat load within enclosed spaces in order to optimize working conditions [e.g., Calvino et al., 2004, ichi Tanabe et al., 2002]. They reach a high degree of precision by incorporating a wide range of variables. Despite the relevance and validity of these metrics, they can hardly be used for an entire city, let alone for an entire region.

Regional studies tend to simplify the variables they examine in order to reach a level of generalization which still allows for valid conclusions without losing relevance [e.g., Mayer et al., 2008, Lin and Matzarakis, 2008]. Many such studies focus on air temperature near the ground. This is due to the fact that observations for the air at these heights are often available, and that this is close to the air with which most humans interact. In the absense of observations, air temperature can be retrieved with relatively high accuracy from numerical weather prediction models.

Despite the elegant simplicity of such methods, it should be noted that air temperature alone neglects the rate of evaporation - particularly of sweat. Due to the high amount of latent energy that sweat can transport away from the body upon evaporation, this is a crucial variable in the human energy household. For this reason, more refined studies often also consider humidity. This is also the reason why most national meteorological services use a combination of air temperature and humidity to communicate the perceived temperature and to produce warnings of dangerous heat levels [e.g., Jendritzky et al., 1990, Staiger et al., 2012, Anderson et al., 2013]. Perceived temperature is considered the best metric for the effects of heat on humans on broad spatial scales due to the ease and accuracy with which it can be derived, as well as to the fact that it accounts for the two most important variables for describing the human energy household without needing to know the factors specific to each individual determining the fine points of heat dispersion for them (i.e. clothing, shade, level of physical activity, etc.).

Once a metric has been decided upon, however, it is still difficult to characterize exactly what aspects of hot weather have the greatest effect on humans. Metrics and norms created for one geographic or cultural setting are not necessarily applicable to others [Lucas et al., 2014]. Also, beyond the temperature metric alone, the duration and frequency of so-called heat waves is important in determining how much humans are affected by hot weather [Anderson and Bell, 2010].

The threshold at which heat is considered to be uncomfortable, or even dangerous for humans, is relative at best. Guidelines are provided by organizations such as the Occupational Safety and Health Administration (OSHA) [Anderson et al., 2013] and the International Organization for Standardization (ISO) [International Organization for Standardization, 2010], as well as numerous weather services [Masterson and Richardson, 1979, Steadman, 1979, Jendritzky et al., 1990, e.g.,], but none of them can claim universal validity because they all, in some way or another, are based on subjective findings concerning comfort and risk. In the end, assessing and quantifying the precise amounts of any thing that damages a human body is impossible, and any attempt to do so would quickly encounter ethical difficulties (for the same reason, for example, there are no absolute thresholds for the amount of force with which a person may be hit on the forehead).

Thresholds are subject to another problem beyond subjectivity: they represent only one dimension of heat load. The effects of repeated, short exposure to high temperatures, for example in saunas, has been shown to have positive effects on humans [Hannuksela and Ellahham, 2001], despite the fact that prolonged exposure to temperatures close to the boiling point of water would surely prove detrimental [National Weather Service, 2014]. Various studies have shown that acute high temperatures for short times affect the body differently than over long periods of time [Thonneau et al., 1998, Gopinathan et al., 1988, e.g.,]. If the weather is very hot during the day, for example, but cool at night, the body can recover and react more robustly to high temperatures on the next day [Laaidi et al., 2012]. Also, the number of consecutive days featuring hot weather are relevant - a succession of hot days, interrupted by cool weather and followed again by more hot days, affects both the human physiology and human behavior differently than a long series of uninterrupted hot days [Robinson, 2001].

This can be summed up as follows: Heat waves are more relevant for human well-being than simple hot weather. Yet although many studies are devoted to evaluating various aspects of heat waves and their effects on humans, there is no universally accepted definition of a heat wave. There is general consensus, however, that both the duration and frequency of heat waves are relevant and that these factors should be explored in order to deepen our understanding of the phenomenon. This thesis attempts to do exactly that.

Human well-being: The ultimate, elusive goal

The direct effects of climate change on human well-being cannot be discussed without examining the concept of human-well being. Among the concepts used in this thesis, it is probably the most elusive and hard to define.

The requirements for human well-being have been the discussion of prophets, philosophers, and policy makers perhaps as long as humans have existed. Siddhartha Guatama famously quested for years to find a way to increase human well-being by understanding suffering. Whether or not this account is historically accurate, his ideas show that this question was already being heavily contemplated thousands of years ago. And he was not the first; Guatama built upon traditions and philosophical research that had been developed over the course of many centuries before his time [Strong, 2001]. It could be argued that every religion and political philosophy in the world is centered upon increasing human well-being, although the means and goals of these ideas are far from uniform and in fact diverge wildly from one another.

In modern times, human well-being has often been reduced to the fulfillment of existential needs. This is in part due to the individualism and materialism that have long traditions in many cultures. Another aspect is the ease of availability of metrics concerning materialistic well-being. The United Nations, for example, established the

Millenium Development Goals in 2000 with the intent of ensuring basic living standards for all people, everywhere. They pertained to human health, access to education, gender equality, and environmental sustainability, among others. These goals consisted of several deliverables which showed whether or not each given goal had been reached [Sachs et al., 2005]. The Millenium Development Goals were superceded in 2015 by the Sustainable Development Goals, which will remain valid until 2030 [UN General Assembly, 2015]. Regardless of the feasibility of these goals, or whether they were pursued vigorously enough, they constitute a quantifiable measure of human well-being from an existential perspective.

Other metrics for human existential welfare include the Human Development Index (HDI), which is designed for more continuous evaluation of human well-being. The HDI was designed to quantify well-being in a combined metric including education, life expectancy and income. It uses a metric, rather than a cardinal system in order to classify the level of "development" a given country has achieved [Anand, 1994]. Other statistics, such as the Human Poverty Index, or its successor, the Multidimensional Poverty Index, have used the same basic variables in order to capture human poverty [Fukuda-Parr, 2006, Alkire et al., 2012]. These, however, are somewhat more complex and involve indicators concerning populations' access to other amenities, such as electricity, clean water and cooking equipment. An extension to the HDI, the Inequality-adjusted Human Development Index, attempts to also capture justice in the distribution of quality of life [Hicks, 1997].

These metrics focus primarily on eliminating poverty and offer only limited insights into economically prosperous areas. This is one reason why the gross domestic product (GDP), for example, is such a widely adopted barometer of economic well-being, and - by design or by accident - human well-being by proxy. Economic productivity, especially in economies which trade primarily in currency rather than in goods or services directly, is readily quantified and the main limit on its use in economic questions is reporting accuracy. One could argue that gross domestic product measures the productivity of a country, which in turn allows one to extrapolate the usable income that people can utilize to fulfill their needs. If their basic needs are satisfied - having shelter, food and water - they can use remaining resources for pursuing whatever goals they have - education, liberty, art, the collection of material goods, travel, etc. Gross domestic product has the additional advantage that it can be observed with great granularity. Measuring the value of goods and services produced at a given place is fairly straightforward [Landefeld et al., 2008], especially as compared to other metrics, as we will see in the following paragraphs. This, and the desire of compatibility with past studies, has caused gross domestic product to be extremely popular in studies focused on economics and human well-being.

GDP is not the only available metric, nor is it without problems. For example, the poorest countries in the world have the lowest economic productivity per person [Maddison, 1983]. This is easy to understand, but it can be misleading when trying to draw conclusions across regional boundaries. The same amount of a given currency in one region can have radically different purchasing power in another, depending on the local market conditions. Thus a per capita GDP in one region might enable a (comparably) high standard of living where measured, while in others the same amount of currency would have a low value in the local market. Thus another refinement of GDP is to normalize it based on purchasing power parity (PPP). This compares productivity based on the goods and services that can be bought with the equivalent value [Taylor, 2003]. It has the disadvantage of adding another dimension of complexity to the data collection.

Independent of the accuracy of the economic meaningfulness of GDP, its accuracy for measuring human well-being is severely limited, mainly because was not designed to distinguish between the production of goods and services that increase well-being and those which do not [Kuznets, 1934].

More complex metrics generally attempt to capture more information about the "real" economic well-being of a country or region. The Genuine Progress Indicator, for example, attempts to compensate for the GNP's over-weighting of production by accounting for depletion of natural resources and damage to the environment. It also incorporates quality of life indicators, such as the costs of crime and the benefits of leisure time and volunteer work [Talberth et al., 2007]. Nonetheless, the Genuine Progress Indicator is primarily an economic statistic of well-being.

Other metrics represent the philosophy that well-being can come from other sources above and beyond economic prosperity. The World Values Survey is an ongoing project with the goal of understanding the views and values of people aroud the world, aggregated to national levels in order to understand what these populations value and desire in life. Its findings highlight not only the fact that economic well-being is not necessarily the most highly valued type of well-being for people around the world, but also the general diversity of opinions concerning what constitutes well-being in the first place [Minkov and Hofstede, 2010].

While the World Values Survey attempts to understand human well-being in a theoretical sense, others attempt to measure it by using additional indicators, not all of which are purely existential. The Social Progress Index, for example, investigates three broad categories of human well-being: basic human needs, foundations of well being, such as access to education, ecosystem stability, etc., and opportunity, including freedom of choice, inclusion in society and access to contraception [Porter et al., 2015]. The Social Progress Index is joined by a suite of other statistics, e.g. the Global Peace Index [Global Peace Index, 2008], the Gender-Related Development Index, and the Gender Empowerment Measure [United Nations Development Programme, 1995], all of which attempt to include not only the economic components of welfare, but also elements which are higher on the existential ladder, mainly from the perspective of seeking justice and/or equality according to the values of those who create the statistics.

Yet other metrics attempt to measure justice not only at the present time, but also inter-generationally. The Happy Planet Index, for example, measures not only perceived human well-being, but also life expectancy and an area's environmental impact. Thus high standards of living, produced at the cost of future welfare, can lower this score [Abdallah et al., 2009]. The Organisation for Economic Co-operation and Development's (OECD) Better Life Index operates under a similar principle, but is somewhat more nuanced and complex in its approach, incorporating many additional topics, albeit only for member states [Kasparian and Rolland, 2012].

Many other metrics are available with varying goals and focuses. In parting, however, one more group should be considered: Metrics quantifying human well-being with their focus specifically on happiness. Perhaps ironically, few statistics with this thematic focus are available on wide spatiotemporal scales. Gross National Happiness, a statistic combining sustainability, culture, environmental conservation and good governance across nine domains and 151 variables, focuses specifically on measuring development with the goal of maximizing happiness [Bates, 2009]. It has since inspired work within the United Nations to measure, record, and where possible to increase happiness on a national level worldwide [United Nations General Assembly, 2013].

Openness in science

The previous chapters have outlined the barest contours of the dangers presented by climate change, its immediate impacts on humans, and the interconnectedness of human well-being and climate change. The following will be devoted to the methodology used in this thesis, beginning with a discussion about its general approach to scientific work.

Mankind currently stands at a crossroads. The global disparity between the rich and the poor creates unrest and leads to unsustainable consumption patterns [Scruggs, 1998]. High populations place large strains on resources [McLellan et al., 2014]. To make matters worse, anthropogenic climate change has just begun to run its course and is likely to negatively impact ecosystems and human life for many generations to come [IPCC, 2014b]. In short, mankind stands, as a species, before the largest challenge it has collectively faced as yet. Willing or unwilling, we are involved in a struggle for the survival of our way of life.

Climate and human systems are deeply and complexly intertwined. Human activities help set the pace for climate change, even if they are potentiated by iteracting with complex elements outside of our control (e.g. land use change modifies the biosystem's capacity to bind and store carbon, as well as changing the Earth surface's albedo, which in turn influences the amount of thermal energy absorbed from sunlight) [IPCC, 2014b]. The mechanisms behind anthropogenic climate change are just as complex. Lowered economic productivity, for example, can reduce the amount of electricity consumed and thus the amount of fossil fuels burned in a given region [Lotfalipour et al., 2010], but the resultant poverty can lead to deforestation in order to utilize the energy stored in wood [Zulu and Richardson, 2013]. This in turn can release carbon and upset the local ecosystem's ability to absorb carbon in the future [Post and Kwon, 2000b]. The same arguments could be made for virtually every area - inefficient production techniques require more resources, but in many cases increasing efficiency leads to higher resource consumption due to higher production [Binswanger, 2001].

There are no simple solutions to these problems, and many of them are not technological, but rather of social nature. How do we decide to live and consume in an age where, for an increasing portion of the population, material well-being can be readily bought, and the potentially devasating impacts of one's behavior are so far away that they are unknown or at least easily ignored? Can we decide to sacrifice luxuries at the present in order to preserve them for the future, or in order to allow others to use them, whom we may not know or be related to, whom we may never meet because they do not yet exist? And can we trust others to do likewise? If our value system does not reward such behavior, acting sustainably has no cognitive result other than producing disadvantages for us alone. For many, this is an accurate description of the current situation; our value system asks the question, "What's the point?"

Questions of this nature have an enabling component in technology and information, yes, but they are also – perhaps primarily – dependent on decisions made by people, many of whom are guided by their perceptions of social contracts. If these social contracts are not intact or not existent, they have no incentive to fulfill them.

Thus living sustainably requires not only finding new ways of fulfilling people's needs. It also involves developing new strategies of consumption and production, as well as new paradigms of perceiving well-being [Robin and Poon, 2009]. It involves developing and implementing technologies that allow us to live in balance with the resources that we can appropriate now, without subtracting from the resources that will be available in the future [Chu and Majumdar, 2012]. It also requires developing a society in which we share with our ecosystems and with each other, and in which we follow the belief that it is worthwhile to do so and that others will do so as well [Padilla, 2002]. Innovation is needed across the board - in our culture, in our incentivization of various consumption patterns, in our understanding of the natural world and our discovery of technical solutions which allow us to simultaneously live well and to live in harmony with our environment.

These topics all go beyond the scope of this thesis, or of any single work. But put simply, it is important that we, as humans, work together to build a better way of living and a better world. Science is essential in this endeavor, and every contribution to this idea, however big or small, helps to make it reality.

Presented through this lens, it becomes clear that openness in all areas - and especially in science - is essential. We have so much need for collaboration and new ideas that we simply cannot afford to not be open. The transparency to scrutiny that openness provides raises the quality of scientific work. At the same time, it acts as an enabler for others. Making work transparent, understandable and reproducible ensures high quality and inspires others to develop ideas of their own.

There is a long tradition of transparency and openness in science. Peer review has been an essential part of the scientific process, in various forms, for centuries [Benos et al., 2007]. However, it has never been as easy - and its absense as inexcusable - as now. In the age of computers, ideas, data and algorithms are some of the key components in cutting-edge breakthroughs. In some areas, it is possible to perform high-quality scientific work without ever gathering data in the field or working in a laboratory at all. Data transfer is not free, but for most of the developed world it costs almost nothing [Van den Bossche et al., 2011]. Algorithms cannot be performed instantly, but their instruction sets can be communicated easily and executed at speeds unimaginable a mere decade ago. As far as information and algorithms are concerned, we live in an age of plenty. The technology exists - and is in use - to perform computational tasks on miniscule budgets that formerly belonged in the realm of high-power users. Even computational fluid dynamics, protein folding, multidimensional signal analysis, and other such complex tasks, could potentially be planned and executed from the poorest countries in the world. Through the power of the Internet the algorithms required can be transferred to faraway supercomputing clusters and executed on data which is already there.

Lowering the barriers to doing so is, arguably, even more important than investing in basic enabling technologies. Anything which keeps people from feeling able to contribute their ideas to the betterment of our species is worthy of elimination. If we can increase standards of living in the developing world, so that people can think less about their basic needs and more about their long-term well-being, we should do so. If we can lower costs for participating in science - especially such artificial and arbitrary costs as those for data or software - we should do so. If we can make low-level algorithms available which can be used for further scientific work, we should do so. This enables scientists to focus on what they want to study, rather than on tinkering with the mechanics of it. A scientist working on atmospheric dynamics should not have to worry about data encoding, for example, any more than a journalist should have to worry about the manufacture of paper or ink. And data - the raw material needed for scientific work - should be made available, if at all possible, so that we can find those jewels hidden inside it that can increase our quality of life.

Democratizing science isn't only the right thing to do. It is a smart move in terms of survival. We cannot afford to squander the resources offered us in the form of millions of untapped minds. Therefore, openness in science must be a priority.

Another crucial reason for openness in science is the magnitude of the challenges we face. We need high quality science and this requires transparency. In a world where algorithms have reached levels of complexity which are difficult to fathom for some of our best minds, it is important that the single components that compose them are understandable. This importance is compounded by the trust we place in these algorithms. They govern traffic lights [Kulkarni and Waingankar, 2007]. They steer automated vehicles [Petit and Shladover, 2015]. They regulate nuclear power plants [Kothare et al., 2000]. For many people, they stimulate the beating of their hearts [Jee et al., 2010]. If we lose access to the inner workings of these algorithms - or if we lose the right to modify them to fit our needs - we entrust ourselves as a society to those who own these proprietary instruction sets. History has proven time and time again that such a consolidation of power is unwise.

Openness in science also ensures reproducibility. Today, much scientific work takes place entirely in computers. This opens new possibilities in exposing our work to external scrutiny. Whereas before, long journeys or expensive laboratories were often required in order to reproduce even the best described experiments, today we can - in equivalent fashion - allow others to duplicate our laboratories and materials and then check the results for themselves. It is also possible that they can make variations on our experiments and come to new conclusions. This is only possible, however, when all necessary materials - the full stack, so to say - are open to scrutiny and use by others. This includes not only algorithms, but also data as well.

These are noble goals, but many feel powerless to realize them. After all, not all scientists collect data which they can make available to others. Not all are able to develop algorithms or write code which others can use. However, this is no cause for disenchantment. Climate change is caused primarily by individual molecules of carbon dioxide which persist in the atmosphere. Each molecule is relevant, even if the concentrations are miniscule - parts per million worldwide. Our contributions, however small, also have long lifespans within the scientific community and a lasting cumulative impact.

How can an individual encourage openness? There are many ways. Many data programs which collect information on a large scale are funded in the hopes that the research will have a high impact. Using these data sets, when possible, raises their citation scores and demonstrates to funding agencies that that and similar research is worthwhile. Open software is also a powerful method of encouraging openness. For those who are able to contribute code or otherwise participate in its technical development, furthering open software can be straightforward. For those who cannot, donating to good projects, communicating desired features, or reporting bugs can contribute as well. And finally, using open software and reporting this to others makes it clear that open software can produce quality results, thus battling common misconceptions which prevent its adoption and lock in proprietary solutions. Therefore, even the mere use of open data and software furthers the principles of openness and aids in anchoring it in scientific work and in the use of computers in general.

The work in this thesis was completed according to these ideas. Data was sourced from open projects - climate data from the European Centre for Medium-Range Weather Forecasting [Dee et al., 2011], demographic data from Eurostat [Eurostat, 2014a,b,c] and Global Rural-Urban Mapping Project [Center for International Earth Science Information Network - CIESIN - Columbia University; International Food Policy Research Institute - IFPRI; The World Bank; Centro Internacional de Agricultura Tropical - CIAT, 2011], and economic data from the Penn World Table [Robert C. Feenstra, Robert Inklaar, Marcel Timmer, 2013]. All data manipulation and analysis was executed in the Linux operating system. Simple data retrieval and sorting were most often executed using the POSIX/UNIX suite of tools. Complex algorithms needing fast execution or operating on large amounts of data were performed using Python or GRASS GIS. Statistical analyses were executed in the R statistical computing environment, using a number of different packages, most of them standard components of the R core implementation. Data visualization and final analysis were conducted with matplotlib in Python and ggplot2 in R. The articles were written in LaTeX and the manuscripts and source codes published on Github.

It is my hope that scientific work in this manner - in the open, as I have striven to do in the coures of this thesis - will increase even more in commonality, ease and accessibility in the future than it is now.

Research approach

The previous chapters have highlighted the difficulties of approaching the topic of this thesis. Not only is perceived temperature difficult to quantify, measuring its effects on the elusive concept on human well-being is difficult. It is for this reason that one of the larger challenges in this work was determining what aspects of these ideas should be studied, in what detail, and how. This chapter will show how this was done. The next will describe the structure of the remaining material which implemented this research design in the form of papers that have since been published in or submitted to scientific journals.

The first question to be investigated was whether climate change was indeed having a tangible impact on perceived temperature. As described in previous chapters, several metrics came into question in order to quantify this variable. Due to the global scale of the subject - and the feasibility of its representative computation on a global grid - the metric heat index was chosen. It was used to confirm that perceived temperature has indeed changed in the course of the last decades, both in mean magnitude and in distribution across the globe.

The next study investigated whether the changes in heat index had measurable effects on human health. This presented further difficulties in the form of the available data. Accurate and spatially highly resolved data series on a global scale are simply not available. Excellent data is, however, available for Europe from Eurostat. The tradeoff here was that the thematic resolution was fairly low. Deaths could only be traced over the course of the entire year, so their temporal proximity to heat events could not be extracted from the data. Additionally, although data is available for various causes of death, these are aggregated to country levels, offering only a very rough spatial resolution. A compromise was found by using the entire number of deaths in a single year. These data were available for all NUTS3 regions. Additionally, due to the manifold mechanisms by which heat can act detrimentally on human health, the loss of information through the lacking causes of death were considered noncritical. Exhaustion due to high heat could lead directly to heart failure, for example, but whether or not such a mortality would be accounted to heat is up to the coroner in question. Additionally, groups which are especially at risk for health detriments due to heat are often also sufferers of chronic health conditions - the elderly, for example, are especially vulnerable, yet for that reason a heat event which is the deciding factor in their death may not be attributed with causing it. Other potential causes of mortality due to heat - inattentiveness while driving, for example, due to heat exhaustion, which causes a fatal traffic accident - would not be attributed directly to heat. Therefore, in order to preserve all the components of heat as a heavily ramified signal, all mortality was included in the analysis.

After confirming that increasing heat is indeed having effects on human health, the final study examined whether these effects were also measurable in the global economy. The effects of rising heat on economic growth were measured using economic data from 105 countries over the last two decades. Due to the large spatial coverage of many countries, and also because of their spatially heterogeneous distribution of population within their borders, values for heat index were aggregated using population-weighted spatial averaging. For this, population data from the Global Rural-Urban Mapping Project was used in order to weight the heat index values within each country. Using this data, it was possible to confirm that rising perceived temperatures have had a dampening effect on growth around the world in previous decades.

Thesis overview and structure

In this thesis I use a novel approach to evaluate the effects of rising perceiving temperature in the course of climate change on human well-being.

In chapter 1 I detail the theoretical background and research landscape of heat in the context of climate change and its effects on humans. I showed the strengths and shortcomings apparent in the literature, as well as the fundamental difficulties of approaching the topic from an analytical point of view.

In chapter 2 I analyze perceived heat over the course of the last few decades by producing a global, highly resolved data set of perceived temperature near ground level. This is introduced in the form of a paper which describes the data, its production and preliminary analyses showing its basic implications, as well as how the distribution of heat has changed from a human perspective worldwide. I show that heat events, when classified using a simple, health-based scheme, have increased in frequency and intensity worldwide and that this can be felt in the world's population centers.

In chapter 3 I examine the effects of heat events on human mortality in Europe. NUTS3 regions are partitioned on the basis of several criteria: their climatological characteristics, their demographic makeup and their economic productivity. The effects of hot weather are analyzed by means of panel regressions, examining the frequency, intensity and duration of hot weather, respectively. The results show that hot weather does indeed lead to higher mortality, and that significant effects can be found for different components of hot weather for different groups.

Chapter 4 investigates the effects of hot weather on economic growth worldwide. Here I also use panel regressions to distinguish between different classes of country based on their economic productivity and simple climatological attributes. The findings indicate that heat plays a tangible role in economic growth for many countries worldwide. They are consistent with the results presented in chapter 3 in that some subpopulations are more affected by heat than others.

The thesis is concluded in chapter 5, where I provide a general overview of the investigations conducted and a synthesis of their results. I show what we can learn from the data and information gleaned during this research and discuss their social and environmental consequences. I also outline the limitations to the approaches used and detail how further work can continue to increase our understanding of the dynamics and processes at play here. Additionally, I outline how the work conducted in this thesis could be extended in the future and translated into higher-impact tools which could assist in real-time heat management, as well as mid-term strategic planning for decision makers.

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Chapter 2

Perceived temperature in the course of climate change: an analysis of global heat index from 1979 to 2013

Published in Earth System Science Data

doi:10.5194/essd-7-193-2015

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Introduction

The essential cause of climate change is the additional entrapment of thermal energy in the earth's many natural systems through carbon dioxide from anthropogenic sources. The speed at which this is occurring is, on climatological and geological timescales, extremely rapid, often requiring faster adaptation than would be expected under normal circumstances.

This additional heat energy has manifold consequences, many of them indirect. All of them, in one way or another, affect humans. For example, additional heat modifies the earth's water household, reducing agricultural yields and in this way affecting human health and well-being [Calzadilla et al., 2010]. More directly, additional heat load has been shown to affect the economy by reducing worker productivity through requiring workers to work more slowly and take more breaks [Kjellstrom et al., 2009]. Extreme heat can have serious health consequences, especially among the sick and the elderly. In the last decade, more than 10 000 deaths in a single month in France were directly attributed to a heat wave [Poumadère et al., 2005]. This list could easily be expanded to include other events and regions, and several studies have shown not only that extreme heat events can be expected with higher frequency and intensity but also that heat load in general should increase in the future [Beniston, 2004, Schär et al., 2004, Intergovernmental Panel on Climate Change, 2014].

Many studies have analyzed the effects of climate change on global temperatures and their distribution in space and time [e.g., Vose et al., 2005, Diffenbaugh and Ashfaq, 2010, Diffenbaugh and Scherer, 2011, Alexander and Arblaster, 2009, Meehl et al., 2009, Smith et al., 2005, Sherwood et al., 2008]. They show that changes in the earth's thermal energy household affect the flow of both latent and sensible heat and are thus the most directly relevant for human physiology. The body rids itself of thermal energy partially through the evaporation of sweat. This process becomes less efficient with higher humidity. For this reason, most metrics that measure heat exposure take both temperature and humidity into account. For example, the wet-bulb globe temperature (WBGT), which incorporates the effect of temperature, humidity, wind speed and radiation into a metric for heat stress in humans, has been used in several health and safety standards measure heat loads and prevent heat illnesses [e.g., International Organization for Standardization, 2010, National Institute for Occupational Safety and Health, 1986]. Although WBGT is an accurate metric for heat load on humans, the number of variables needed to compute it hinder its applicability for regional- or global-scale applications. Other examples include, among others, the Klima-Michel model for apparent temperature, which uses not only temperature, wind speed and air moisture but also activity level and clothing to determine the apparent temperature for an average person [Jendritzky et al., 1990]. In the field of meteorology, a much more common metric is apparent temperature, measured using the heat index [Anderson et al., 2013]. This metric has seen wider adoption in the health and meteorological communities due to its dependence solely on humidity and temperature [e.g., Perry et al., 2011, Kysely and Kim, 2009, El Morjani et al., 2007, Burkart et al., 2011, Basara et al., 2010].

We present a new data set of globally gridded heat index values computed from reanalysis results for the years 1979–2013. These values are aggregated on several temporal and spatial scales. The data are presented in the context of global climate change and its direct effects on human health. We several temporal and spatial scales. Furthermore, we describe the effects of climate change on the global distribution of heat index and investigate these effects for different countries through the study's time period. The data are available for further use by the scientific community [Lee, 2014]. It is our hope that these data can serve as a basis for further studies to evaluate and understand changes in heat index over the course of climate change and how it impacts different areas of human society.

Material and methods

Data source

High-quality, consistent data measured at the same place over climate-scale time periods are extremely difficult to obtain. For this reason, we use reanalysis data in order to create the data set on heat index.

Reanalysis data are not an equivalent to observation data and should be used carefully [Thorne and Vose, 2010]. Nonetheless, for our purpose, reanalysis data seem to be the most appropriate choice. A priority is to produce spatially and temporally continuous data of a consistent quality for the entire globe over a long period of time. In addition, as many high-quality observations should be incorporated into the data as possible, without introducing anomalous signals into the data, for example through changes in observation techniques and shifts in observation locations.

The ERA-Interim reanalysis by ECMWF is well suited for this task. It uses the same data assimilation system and dynamic modeling core over a long period of time – from 1979 extended up until the present. The model used to produce the reanalysis, the ECMWF's Integrated Forecast System (IFS), uses three fully coupled components for atmosphere, land surface and ocean waves. This improves accuracy especially for areas surrounded mostly by ocean. Because the model was used to produce a reanalysis, which did not have to be published in a time critical fashion, observations from all over the globe could be assimilated, even if they were only available after a normal forecast model's cutoff time. These observations can be quality-controlled before being assimilated into the model. Using a model rather than, for example, a simpler interpolation approach makes it possible for the model to propagate information obtained through observations through variable domains, space and time [Dee et al., 2011]. All of these criteria made ERA-Interim an intuitive choice as a basis for our study [Dee et al., 2011].

The ERA-Interim reanalysis used four assimilation cycles per day, at 00:00, 06:00, 12:00 and 18:00 UTC. The original data were produced on a reduced Gaussian grid with approximately uniform spacing for surface fields of 79 km [Berrisford et al., 2009].

We use data from the entire available time period of 1979–2013. The data were downloaded after interpolation from the Gaussian onto a regular $0.75° \times 0.75°$ latitude–longitude grid to ease processing in various GISs. Two variables were downloaded: air temperature and dew point temperature, both at 2 m height above ground.

Computing gridded heat index

Heat index has been computed using a variety of algorithms in different studies. We chose the currently operational method used by the National Weather Service (2014a), which was developed by Rothfusz (1990) based on work by Steadman (1979), because it is used widely in the operational production of weather warnings in real-life situations and demonstrates the best agreement among heat index algorithms with the original equations [Anderson et al., 2013]. All calculation was done using GRASS GIS [GRASS Development Team, 2015].

The chosen algorithm uses relative humidity and temperature in °F at 2 m above ground as input. While temperature is given in the ERA-Interim reanalysis data, relative humidity had to be calculated. Of the many possible ways to compute relative humidity from dew point temperature [see, for example, Lawrence, 2005], we decided to follow the methodology of the National Weather Service [Murphy, 2006] for the sake of consistency with the method of computing heat index. It is computed as follows:

$$\mathrm{RH} = \left(\frac{112 - 0.1T + T_\mathrm{d}}{112 + 0.9T}\right)^8, \tag{2.1}$$

with RH as relative humidity, T as temperature in °C and T_d as dew point temperature in °C.

Heat index was computed using an algorithm beginning with a simple approximation:

$$\mathrm{HI} = \frac{T + 61.0 + ((T - 68.0) \cdot 1.2) + (\mathrm{RH} \cdot 0.094)}{2}, \tag{2.2}$$

where HI is heat index in °F, T the temperature in °F and RH the relative humidity.

If HI is $< 80\,°\mathrm{F}$, this approximation is kept as the final result. Otherwise, it must be computed with a more precise regression:

$$\begin{aligned} \mathrm{HI} = & -42.379 + 2.04901523 \cdot T + 10.14333127 \\ & \cdot \mathrm{RH} - 0.22475541 \cdot T \cdot \mathrm{RH} \\ & - 0.00683783 \cdot T^2 - 0.05481717 \cdot \mathrm{RH}^2 \\ & + 0.00122874 \cdot T^2 \cdot \mathrm{RH} + 0.00085282 \cdot T \cdot \mathrm{RH}^2 \\ & - 0.00000199 \cdot T^2 \cdot \mathrm{RH}^2 + \text{adjustment}, \end{aligned} \tag{2.3}$$

with the adjustment conditionally given by

$$\begin{cases} \frac{13-\mathrm{RH}}{4} \cdot \sqrt{\frac{17-|T-95|}{17}} & \text{if RH} < 0.13 \text{ and } 80 < T < 112 \\ \frac{\mathrm{RH}-85}{10} \cdot \frac{87-T}{5} & \text{if RH} > 0.85 \text{ and } 80 < T < 87 \\ 0 & \text{else} \end{cases} . \tag{2.4}$$

Limitations of the approach

It should be noted that the heat index, which was created for the purpose of measuring physiological stress due to high heat loads, is not adapted for measuring stress due to coldness. Also, above a certain level the heat index is oversaturated, so that no additional information can be gained from it. For this reason, we rounded extreme heat index values into the range of 40–140 °F in our visualizations. This corresponds with the lower bounds of the heat index equation [Anderson et al., 2013] and the rough upper bounds of danger levels derived from heat index [National Weather Service, 2014b]. The published raw data, however, are not rounded, so that users can decide whether or not they wish to reduce its value range [Lee, 2014].

Temporal and spatial aggregation

The primary reason that heat index is so relevant in the context of climate change is its direct and indirect effects on human health and the anthropogenic systems connected to it. Thus, we expect that our data on the heat index can and will be used in many further studies, in which they will be connected to other data.

The heat index is calculated for each grid point and for each point in time for which the ERA-Interim reanalysis is available. However, using the calculated heat index in further studies usually implies that data on a daily or even monthly or yearly basis are necessary. Therefore, we aggregated the heat index to daily levels. For each day, the four assimilations were combined in order to produce gridded daily minima, means and maxima. We consider this a good approximation of the nighttime heat index, which represents the daily minimum in most cases; the actual local mean heat index over the course of the day; and the daily midday heat index, which is the maximum in most cases. In addition to producing these daily aggregates, the daily metrics were aggregated to monthly and yearly temporal levels.

In addition to the temporal aggregate, the combination with other data will also make a spatial aggregation necessary in many studies. Other data are often given on a regional or national level. Therefore, we also examine the heat index on the level of countries. For studying the effect on humans and human activities, the heat index in populated areas is especially relevant, as dangerous heat exposure in areas where no people are affected is at most tangentially connected to human well-being.

The Global Rural-Urban Mapping Project (GRUMP) [Center for International Earth Science Information Network - CIESIN - Columbia University; International Food Policy Research Institute - IFPRI; The World Bank; Centro Internacional de Agricultura Tropical - CIAT, 2011] provides high-quality gridded population data. The data set consists of estimates of human population for the years 1990, 1995 and 2000 on a 30 arc-second grid (meaning a horizontal resolution of approximately 1 km) for the entire globe. GRUMP is based on work originally done for the Gridded Population of the World (GPW) data set [Center for International Earth Science Information Network - CIESIN - Columbia University; International Food Policy Research Institute - IFPRI; The World Bank; Centro Internacional de Agricultura Tropical - CIAT, 2004], which was produced by resampling census and survey data for administrative units onto a regular grid. The population was temporally interpolated between sampling points to the above-mentioned snapshot years. GRUMP refined the original data by identifying urban areas with the help of administrative data and nighttime satellite data. Population was then redistributed inside administrative areas to the respective urban and rural areas in order to match the proportion of urban–rural population described by data from the United Nations [Balk et al., 2010].

Because of the large number of changes in administrative boundaries and population distribution in the years following the dissolution of the Soviet Union in 1991, the authors of GRUMP were often forced to combine heterogeneous data sources into their results [Balk and Yetman, 2004]. Although this was done with a high degree of care and in-depth knowledge of each individual case, the uncertainties that this produced prompted us to consider the estimates from 1990 to be the best compromise between quality, consistency and the required accuracy for our analyses. Thus, we only use the GRUMP data for 1990 to aggregate our data to the national level.

Furthermore, for the sake of consistency, we aggregated the population data into current political boundaries [Patterson and Kelso, 2014], rather than adjusting the data to accommodate the modification, addition or dissolution of national borders over time. Therefore, all statements about changes in the climate of given countries in this study should be interpreted as referring to the geographic areas currently officially occupied by the country in question, rather than the possibly dynamic geographic area occupied by the country over the study period.

The following steps were used to aggregate our data to the country level. First, the heat index data for the areas covered by each country were rasterized onto the same coordinate system as the GRUMP data. This made it possible to discretely sum the population inside each country according to the GRUMP estimates. Per-grid-point population weights were produced by calculating the proportion of population within that country that contained the grid point in question, as follows:

$$p_{\text{weight}} = \frac{p_{\text{count}}}{p_{\text{total}}}, \tag{2.5}$$

where p_{weight} is the cell's population weight inside the country, p_{total} the country's total population and p_{count} the population count for the grid point.

The per-country weighted mean heat index was then computed as follows:

$$\text{HI}_{\text{weight}} = \sum p_{\text{weight}} \cdot \text{HI}. \tag{2.6}$$

Weighted means were produced for each country with available data and each temporal aggregation level, as outlined in Sect. 2.

Application: heat index and global climate change

As mentioned above, we expect that the heat index as it is calculated here can and will be used in many future studies. To give some first impression we discuss the change of the heat index between the time periods 1979 and 1999 and 2000 and 2013. Although neither of these periods represents a typical 30-year climate period, this was considered a good compromise which placed the bulk of the data in the 1970–1999 and 2000–2029 climate periods while splitting the data into temporal chunks of similar

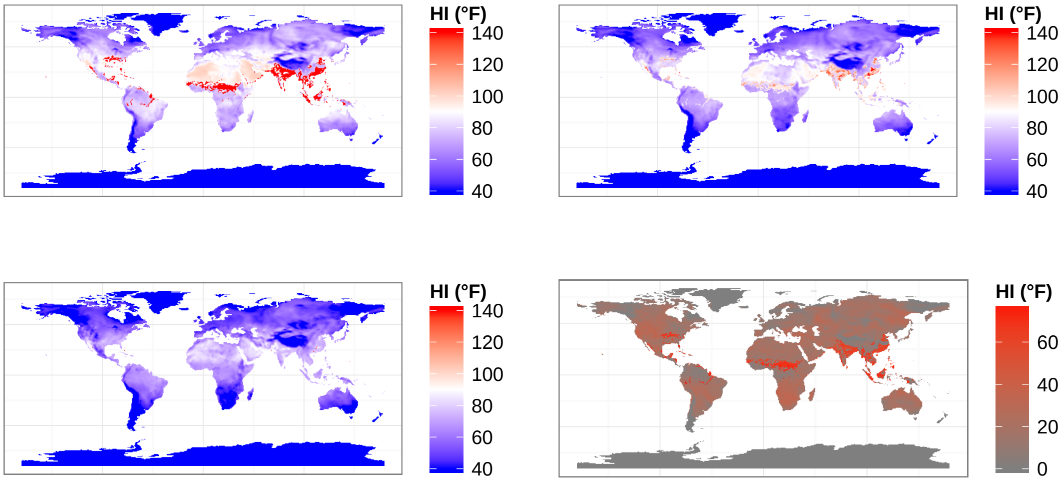

Figure 2.1: Typical heat index for an exemplary day (2 June 1996). Upper left: maximum heat index; lower left: minimum heat index; upper right: mean heat index; lower right: diel range of heat index.

lengths. All data visualization is done using ggplot2 [Wickham, 2009].

Global heat index

Figure 2.1 shows the heat index metrics for the entire globe on a typical day in summer in the Northern Hemisphere. Dangerous heat index levels can be seen both in the daytime maximum, as well as during the night in hot, moist regions near the Equator. The diurnal cycle is especially high for hot and moist regions, high for dry areas in which the temperature fluctuates highly in the course of the diurnal cycle, and low in drier areas with relatively small diurnal temperature cycles.

The change between both reference periods is shown in Fig. 2.2. The maximum heat index shows large changes in both directions for single grid points. This is due to the fact that the maximum heat index for each entire reference period stems from single, significant events that are highly specific in both time and space. This causes spatial shifts in the occurrence of extreme heat index events to produce large deviances between reference periods, similar to the double-penalty problem encountered when computing skill scores for high-resolution forecast models [Mass et al., 2002]. Mean and minimum heat indices increase almost across the globe between both reference

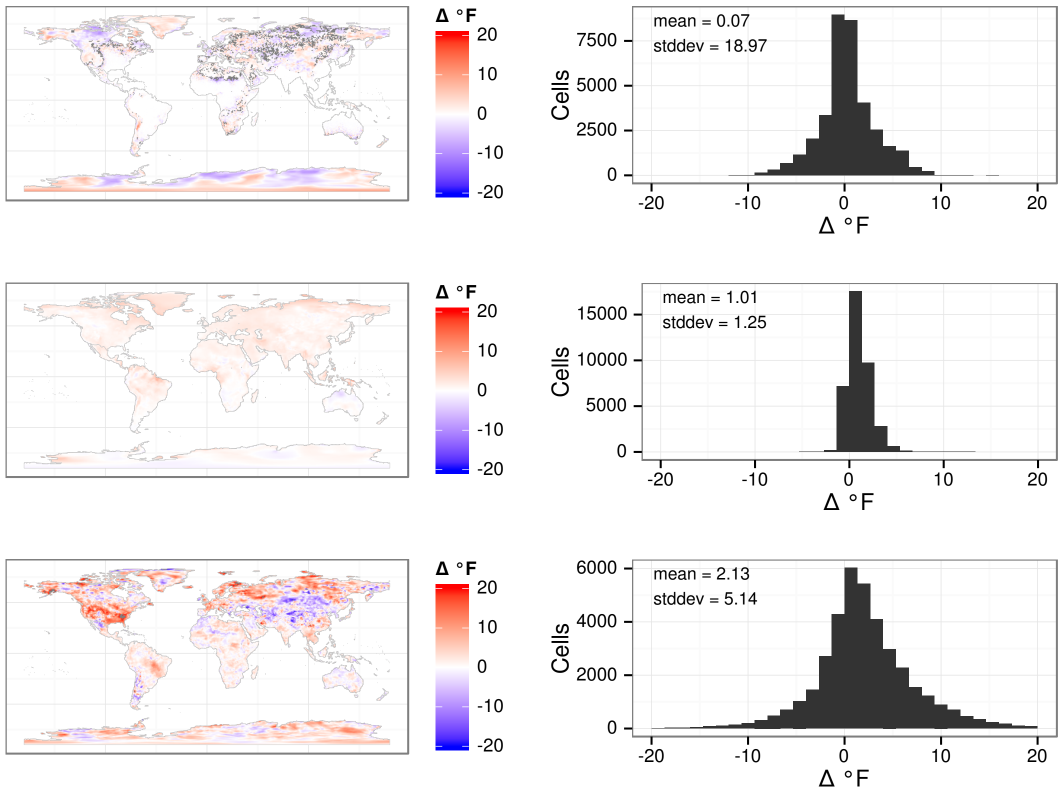

Figure 2.2: Differences between yearly temporal statistics for each reference period (1979–1999, 2000–2013). The left column shows, from top to bottom, the differences in maximum, mean and minimum heat index for the entire year for the entire globe. The right column shows the frequencies of heat index changes worldwide in number of cells for each aggregate statistic. Continents are added for orientation [South, 2011, Bivand and Rundel, 2014].

Table 2.1: Heat index danger levels according to National Weather Service (2014b).

°F	Danger level
> 80	Caution
> 91	Extreme caution
> 103.5	Danger
> 126	Extreme danger

periods, with the most notable differences in minimum heat index over continents in the Northern Hemisphere.

An evaluation of the change in monthly mean heat index across the globe for both reference periods, as shown in Fig. 2.3, offers a glimpse into the temporal distribution of heat index changes in the course of the year. The monthly means of heat index clearly increase across the globe, most visibly at higher latitudes.

One of the most important applications of our data is the evaluation of danger due to high heat loads. We classified danger due to high heat index according to the criteria outlined in Table 2.1.

For each reference period and each of the classification criteria shown above we calculate the probability that the peak heat index of each day exceeds the threshold for extreme danger in each month. Then, we compare the exceedance likelihood between the two reference periods. The results, shown in Fig. 2.4, demonstrate that the likelihood of heat index values reaching levels that indicate "extreme danger" has increased worldwide in every month. South America during southern summer and the Gulf of Mexico in northern summer had especially large increases in likelihood of extreme danger. West Africa also had increased likelihood of dangerous heat index levels the year round, as did northern Eurasia for most months. Most parts of Asia, especially northern Asia, showed increases in heat index throughout most of the year. Two notable exceptions are northern Eurasia and Alaska, which both showed decreases in heat index during northern winter.

Classifying countries according to heat index

Another interesting application of the new data set is the classification of countries according to their heat index climatologies. We use the population-weighted heat in-

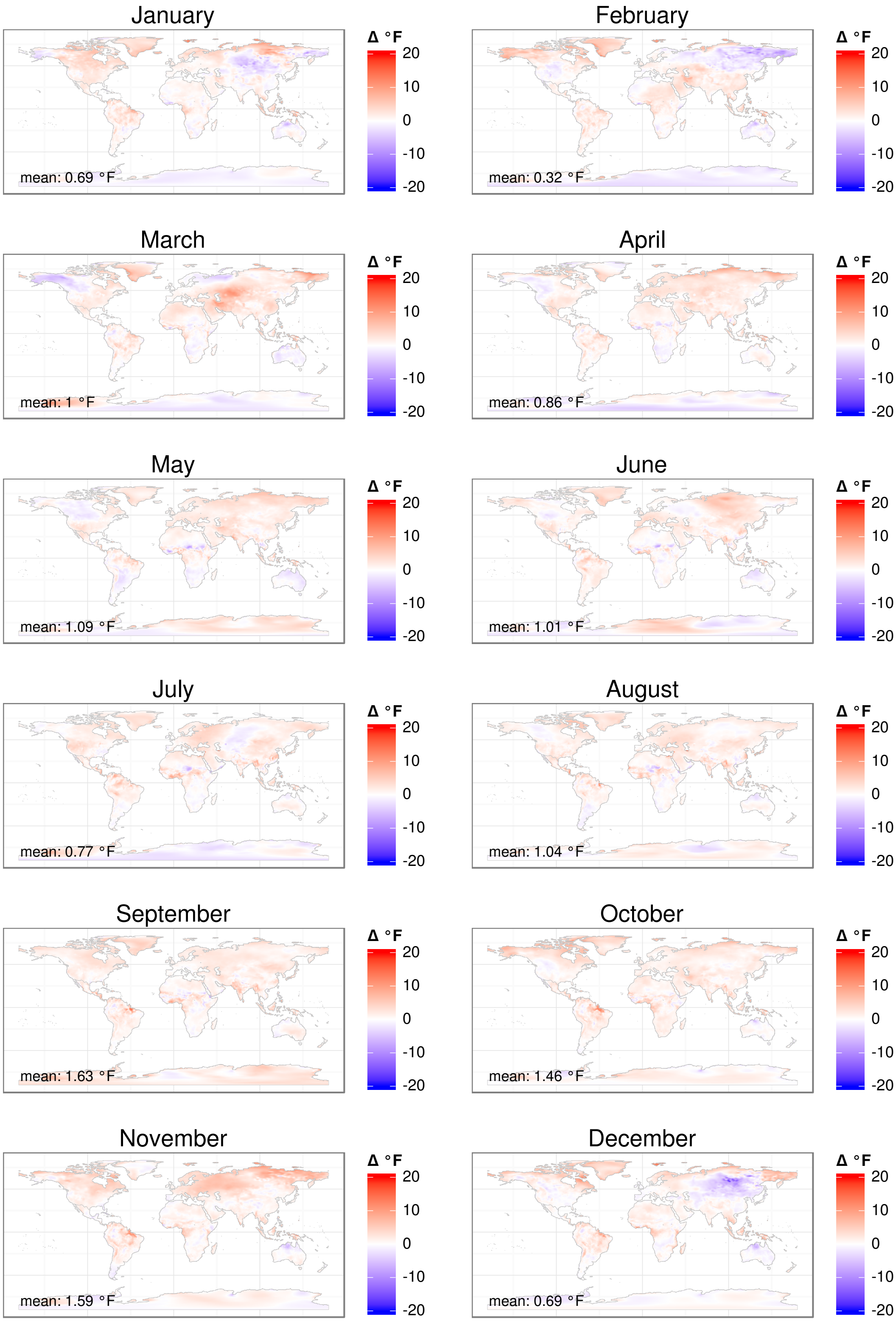

Figure 2.3: Changes between both reference periods (1979–1999, 2000–2013) in monthly mean heat index. The inset numbers refer to the mean increase in heat index for the month in question between both reference periods. Continents are added for orientation [South, 2011, Bivand and Rundel, 2014].

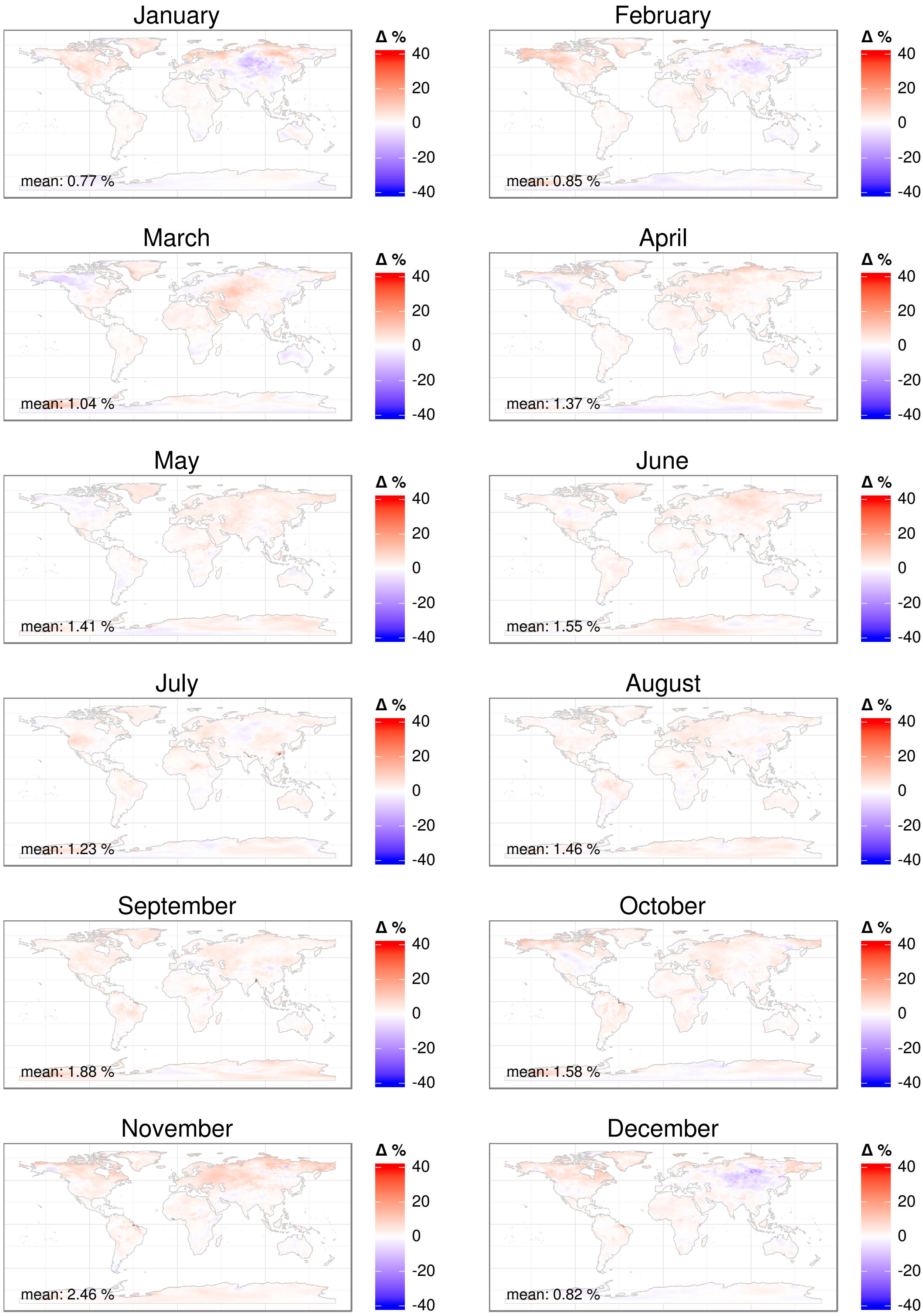

Figure 2.4: Change in the probability that the maximum heat index will exceed the threshold for "extreme danger" for a given day in each month in 2000–2013 compared to 1979–1999 [National Weather Service, 2014b]. Continents are added for orientation [South, 2011, Bivand and Rundel, 2014].

dex minima, means and maxima in each month and apply an iterative *k*-means cluster identification [Hartigan and Wong, 1979], implemented in the statistical software R [R Core Team, 2014]. After each iteration, the sum of squared distance between points in each cluster was examined in order to determine the point at which additional clusters no longer produced useful information [Everitt and Hothorn, 2010, p. 251].

The clustering is applied to both reference periods: eight clusters are created. This number of clusters matched both reference periods well – more clusters did not seem to produce any substantial gains, whereas fewer clusters would have meant a larger sum of squared distance between points inside individual clusters.

The clusters were examined using ordination plots based on the methods by Oksanen et al. (2014). The clusters created by the data for each reference period are similar, but not identical. The changes between both reference periods are shown more clearly in Fig. 2.5. Most changes are in Africa, southern Europe and Asia. A first visual analysis indicates that subtropical heat index climates have expanded away from the Equator and toward the poles. Especially cool, dry or humid areas retain their climatology across both reference periods.

Conclusions

In this paper, we introduce a new data set containing gridded heat index values 2 m above ground for the entire globe at 00:00, 06:00, 12:00 and 18:00 UTC of each day for the years 1979–2013. Due to the widespread use of heat index as an indicator for dangers to human health caused by heat loads, we believe that these data will be of great use in future studies concerning heat stress in the course of climate change. Our data set is new in the sense that it makes heat index values available on a high spatiotemporal resolution and on a continuous grid for the entire planet. We show its potential for further studies by performing some initial, straightforward analyses that provide a first glimpse into the data.

It is shown that, for the two periods chosen for our study (1979–1999, 2000–2013), the distribution of heat index across the globe has changed. The worldwide mean heat

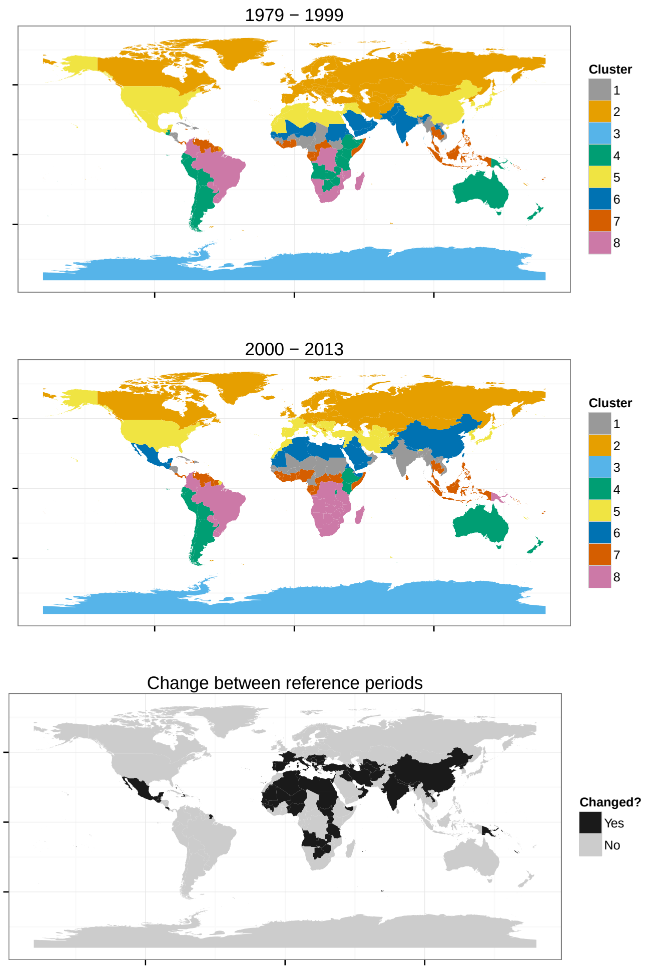

Figure 2.5: Countries and the clusters they were grouped into. The map at the top shows country clusters for the first reference period, and the map in the middle shows county clusters for the second. The map at the bottom indicates whether the cluster that a country was grouped into changed between both periods.

index has risen, both for the entire year and for each month. The likelihood of daytime heat index values that indicate "extreme danger" has also increased across the globe since the 20th century. This analysis is meant as an example usage of these data and could be repeated for different thresholds, with a finer quantile resolution, or focused on more specific geographic areas or time periods in order to obtain more meaningful information.

It is also shown that heat index data can be used for studies on the country level, e.g., for classifying countries into heat index "climate zones". Such a country-level analysis is only a first example of possible ways of using these data. Examining them on a finer spatiotemporal scale and combining them with additional data could reveal more information and aid in analyzing, understanding and predicting the connection between heat index and various components of human systems.

The data are available for general use [Lee, 2014] and the scientific community is encouraged to take advantage of them in studies evaluating heat index, its distribution through space and time, and its connections to and influences on human systems.

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Chapter 3

Influence of heat index on regional mortality in Europe

Submitted to Natural Hazards and Earth System Sciences

Authors: Daniel Lee, Thomas Brenner

Introduction

The global climate is changing, resulting in manifold consequences for natural and human systems. These changes result in a net increase in global mean temperature, but the incrase will be unevenly distributed in time and space [e.g., Vose et al., 2005, Diffenbaugh and Ashfaq, 2010, Diffenbaugh and Scherer, 2011, Alexander and Arblaster, 2009, Meehl et al., 2009, Smith et al., 2005, Sherwood et al., 2008]. The changes will make adaptation in ecological and economic systems necessary, as well as in the behavior of individuals in order to adapt to the new circumstances Intergovernmental Panel on Climate Change [2014].

Being subject to higher heat loads creates problems for several human systems. It affects them directly by modifying the water household and reducing agricultural yields Calzadilla et al. [2010]. It also reduces economic productivity by forcing workers to increase break frequency and work more slowly Kjellstrom et al. [2009]. More directly, additional heat load can cause health problems, especially for the sick and the elderly. In 2003, for example, a heat wave was responsible for the deaths of more than 10,000 people in France alone Poumadère et al. [2005]. The frequency and intensity of extreme heat events is projected to increase in the future Beniston [2004], Intergovernmental Panel on Climate Change [2014]. These facts demonstrate the relevance of research into the effects of heat events, as well as into strategies for mitigating their negative effects.

The increasing occurrence of hot weather in Europe in the context of climate change has been amply demonstrated [e.g. Lee and Brenner, 2015]. A number of previous studies have shown the impact of high temperatures for specific locations [e.g. Burkart et al., 2011, Basara et al., 2010]. However, a thorough analysis of the regional effects of heat on mortality for a large area has yet to be done. This study adds to the existing literature by evaluating the regional effects of hot weather on mortality in Europe. It is proposed that the effect of hot weather on mortality can be identified on a regional level and, furthermore, that the effect of hot weather on mortality varies regionally. In light of the increasing frequency and intensity of heat events in Europe, these insights into the dynamics between heat and mortality can help quantify the risk in various regions associated with high temperatures, identify regions with successful strategies for mitigating these effects and aid in the adaptation and further development of such strategies.

We use the heat index (HI), a common metric in the meteorological and health communities for physiologically relevant heat load on humans, to investigate the effects of hot weather on regional mortality. A generalized method of moments (GMM) panel regression is applied, with regions partitioned according to baseline climatological, demographic and economic criteria. By examining different types of hot weather events, we find that HI has a consistent, significant positive effect on mortality. The mechanisms through which HI affects mortality, however, appear to vary longitudinally across regional subgroups.

Theoretical background

The influence of heat on human health

Heat affects the human body through a variety of mechanisms. For example, thermal stress can lead to cardiovascular mortality Burkart et al. [2011]. In recent decades, heat waves have been associated with pronounced spikes in mortality, especially among the elderly Poumadère et al. [2005]. Urban areas are affected disproportionately by heat waves due to the urban heat island Basara et al. [2010]. These facts, combined with the global processes of climate change, population aging, and urbanization, show that heat plays an increasingly important role in human health.

Yet physiologically, temperature alone is an insufficient metric for heat stress in humans. In fact, the quantification of heat load on humans is a complex undertaking, with the result that there is no standard, unambiguous descriptive metric that can be applied across the board to describe the effect of heat on the human body Perkins and Alexander [2013]. Heat load is caused by the combination of latent and sensible heat. The body rids itself of thermal energy partially through the evaporation of sweat. If humidity is high, this process occurs less efficiently, thus increasing the physiological heat load. For this reason, humidity is often incorporated into metrics that measure heat load on the human body.

A common metric for human heat load that is used in controlled environments is the wet bulb globe temperature (WBGT), because it incorporates temperature, humidity, wind speed and radiation, all of which are relevant for the diffusion of heat from the body [International Organization for Standardization, 2010, National Institute for Occupational Safety and Health, 1986].

While WBGT provides highly accurate assessments of the heat load on the human body, it is impossible to measure on a regional or global scale. This is due to the fact that the many variables it requires fluctuate widely even over short distances. In the field of meteorology, several metrics are available to quantify heat load, issue warnings, etc. Fröhlich and Matzarakis [2015]. A widely used metric is HI Anderson et al. [2013]. This metric enjoys wide use in the health and meteorological communities because it can be computed from the variables humidity and temperature [e.g. Perry et al., 2011, Kysely and Kim, 2009, El Morjani et al., 2007, Burkart et al., 2011, Basara et al., 2010]. Not only are these the most important variables when measuring physiological heat load, but they are also much more spatially homogeneous than the other variables required to compute WBGT and are readily availabe in the outputs of all numerical weather prediction models.

It can be expected that Europe will be strongly affected by increased HI in the future. Not only has HI risen over the past decades, but also the likelihood and intensity of extreme heat events has increased significantly in Europe Lee and Brenner [2015]. Average HI for all of Europe is higher this century than in the last (see figure 3.1).

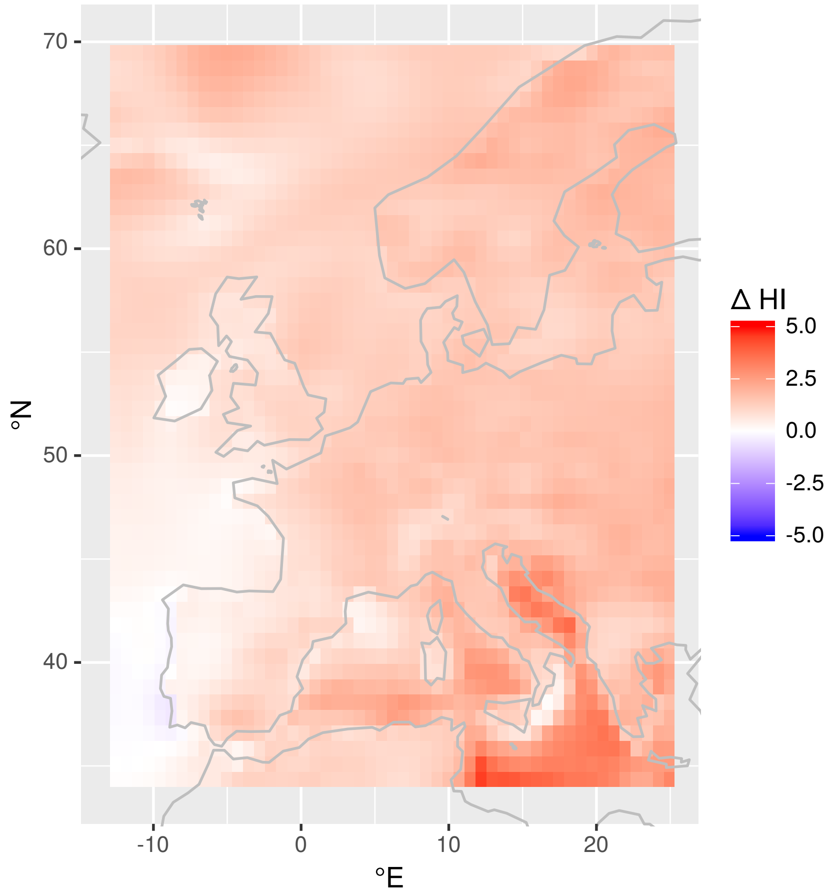

Figure 3.1: Change in average HI over Europe from the 20th to the 21st century.

In contrast to the uniform increase in HI across Europe, the demographic and economic situations that contribute to the effect of HI on humans vary widely. It is to be anticipated that some regions are better adapted to mitigating the effects of high HI than others. In light of these facts, we hypothesize:

1. When viewing Europe as a whole, high HI and extreme HI events significantly increase mortality.

2. Regions in Europe with more elderly populations will be more strongly affected by high HI than regions with younger populations, due to the increased vulnerability of elderly people to cardiovascular mortality when subjected to heat load.

3. Regions in Europe with higher GDP per person will be less strongly affected by high HI than regions with low GDP per person, because people in regions with high GDP per person will generally have more options to mitigate the effects of hot weather. For example, a higher proportion of workers work in modern buildings in these regions and private housing will probably have higher standards.

4. Regions in Europe with high average HI will be affected less strongly by high HI events than regions with low average HI, because their populations use strategies for dealing with heat load (architectural styles which collect cool air in buildings, air conditioning, clothing styles, etc.).

Material and methods

Data

Weather data

HI values were obtained from a global dataset derived from the ERA-Interim weather reanalysis Berrisford et al. [2009] available in high spatiotemporal resolution for the entire planet Lee [2014]. It is provided on a 75 °x 75 °latitude-longitude grid and aggregated to daily minima, means and maxima for each grid point on the globe for the years 1979–2013.

Table 3.1: Heat index danger thresholds, their associated prefixes in the paper's nomenclature and the danger levels they signify.

Danger level	Suffix	Threshold
Caution	caution	80.0
Extreme caution	ext_caution	91.0
Danger	danger	103.5
Extreme danger	ext_danger	126.0

Table 3.2: Variable prefixes used in the paper and the metrics they refer to.

Prefix	Criteria
nrun	Number of waves
longrun	Length of longest waves
cross	Times threshold crossed

These data were classified according to crossed danger thresholds using GRASS GIS GRASS Development Team [2015]. We used the thresholds provided by United States National Weather Service National Weather Service [2014]. They were chosen because of their direct association with HI and their focus on its effects on human health. This produced the four levels of dangerous heat exposure found in table 3.1.

The HI danger categories were regionalized into each NUTS 3 geographic region in Europe using geographic boundaries obtained from the Geographical Information System at the COmmission (GISCO) EuroGeographics [2010]. They were aggregated to a single value per region and time step in the relevant period by computing the spatially weighted maximum HI for each day using GRASS GIS GRASS Development Team [2015].

As is the case with heat in general, the effects of HI are multifacetted and not readily classified. The absolute HI, as well as the number of consecutive hot days and the number of heat waves in general, can all be of interest and are used to varying extents in different heat metrics ([e.g. Meehl and Tebaldi, 2004, Fischer and Schär, 2010, Russo et al., 2014, etc.]). We defined heat waves as at least five consecutive days on which the HI exceeded the chosen threshold. Using this definition, we computed three different metrics to describe heat waves for each danger level (see table 3.2).

The four danger levels for each of the three yearly metrics produced 12 different measures of the annual heat exposure. These were calculated using numpy van der Walt et al. [2011] and pandas McKinney [2010]. To avoid cocorrelation, we used the differences between adjacent categories, rather than the absolute number of times each threshold in that category was exceeded. Thus each measure contains the number of events in its category which exceeded the number of events in the previous danger category.

In the following text, each measure is denoted as the combination of the metric and danger threshold. For example, *nrun_caution* denotes the number of times in a year in which the maximum HI exceeded the caution threshold on at least five consecutive days, whereas *nrun_ext_caution* denotes the number of times in a year in which at least five consecutive days had a maximum HI that exceeded the extreme caution threshold, subtracted by the number of times in the same year in which at least five consecutive days had a maximum HI which exceeded the caution threshold.

Demographic data

Demographic data was obtained from Eurostat containing annual mortality Eurostat [2014a], population by broad age groups Eurostat [2014c] and GDP Eurostat [2014b] for all NUTS 3 regions for the period 2000–2012. The demographic data was mapped to the NUTS 3 geographic regions using NUTS ID and GISCO keys from Eurostat's metadata server Reference And Management Of Nomenclatures (RAMON) Eurostat [2013].

Mortality and GDP data were normalized in each region by that region's population. For the calculation of elderly proportion individuals over 64 years of age were considered elderly. The data was also cleaned by removing time points at which any data were missing and by removing duplicated regions. Finally, the demographic data was joined with the HI data and all following steps were conducted in the statistical analysis environment R R Core Team [2014].

Table 3.3: Analyzed subgroups and the criteria used for sorting regions into them.

Group	Criteria
All regions	None
Regions with young populations	<0.18% of population is elderly
Regions with elderly populations	$\geq$ 0.18% of population is elderly
Regions with low GDP	Annual GDP per person <€ 23300
Regions with high GDP	Annual GDP per person $\geq$ € 23300
Regions with low mean heat index	Mean heat index <49.3
Regions with high mean heat index	Mean heat index $\geq$ 49.3

Regression approach

We conducted a panel GMM regression, which allows testing for causality through the use of instrument variables Croissant and Millo [2008]. Following this practice, we used lagged variables as instruments. Time and regional fixed effects were included in the estimations.

We analyzed the idiosyncratic effects predicted in our hypotheses by partitioning the data into different groups. Regions were partitioned according to elderliness, GDP and mean HI, as shown in table 3.3. Regions were partitioned at the median of the variable in question in order to create groups with similar sizes.

Results were cleaned and formated for interpretation using [Wickham, 2009, Bivand and Rundel, 2014, Bivand and Lewin-Koh, 2015, Hijmans, 2014, Pebesma and Bivand, 2013, Harrell et al., 2016, South, 2011].

Results and discussion

Overall, this study confirms the proposed hypotheses. High HI has a significant, positive relationship with mortality in almost all cases. In the following sections, the results are discussed in the context of the individual hypotheses. The complete results for all regressions are provided in the appendix.

Table 3.4: Panel GMM regression results for mortality as a dependent variable. Results are shown for each variable with p-values in brackets.

	All regions
n regions	1054
cross_caution	**3.635e-06 (0.006591 ***)**
cross_ext_caution	**4.769e-05 (0.03432 *)**
cross_danger	**3.564e-06 (0.02359 *)**
cross_ext_danger	**5.789e-06 (0.006443 ***)**
longrun_caution	2.351e-06 (0.5193)
longrun_ext_caution	**1.176e-05 (0.03325 *)**
longrun_danger	**1.092e-05 (0.04302 *)**
longrun_ext_danger	1.233e-05 (0.08342)
nrun_caution	**8.76e-05 (9.741e-06 ***)**
nrun_ext_caution	4.203e-05 (0.2391)
nrun_danger	2.832e-05 (0.2259)
nrun_ext_danger	1.66e-05 (0.5065)

Hypothesis 1: HI events lead to increased mortality in Europe

Our first hypothesis proposed that in Europe, as a whole, HI events have a positive relationship to mortality.

Table 3.4 provides clear confirmation of this hypothesis. All measures for regional HI are positively associated with mortality. The null hypothesis can be rejected for seven out of the twelve tested variables.

The results for the different variables show interesting variations. While the length of a heat wave and the number of heat waves have insignificant effects on mortality for some heat thresholds, the number of times in a year that the threshold is crossed significantly affect mortality in all cases. In the case of the number of heat waves the category "caution" is highly significant.

Clearly, high HI leads to greater mortality, as shown in the significance of especially the *cross* variables. However, the lower significance of especially the *longrun* variables suggests that this effect can be observed independently of the temporal coherence between high HI events.

Additionally, the high significance of *nrun_caution* suggests that heat waves are related to mortality through mechanisms above and beyond the simple crossing of dan-

Table 3.5: Panel GMM regression results for mortality as a dependent variable. Regions are sorted into groups using criteria based on elderly proportion of population. Results are shown for each subgroup and variable combination with p-values in brackets.

	Regions with young populations	Regions with elderly populations
n regions	581	675
cross_caution	**5.953e-06 (0.009168 ***)**	**6.879e-06 (1.782e-05 ***)**
cross_ext_caution	8.708e-08 (0.9765)	6.047e-06 (0.07236)
cross_danger	**4.171e-06 (0.0122 *)**	**8.308e-06 (0.007034 ***)**
cross_ext_danger	4.494e-06 (0.1189)	8.537e-07 (0.7566)
nrun_caution	2.188e-05 (0.5534)	**0.0001149 (1.101e-07 ***)**

ger thresholds. A large number of heat waves that exceed the "caution" threshold has a highly significant relationship with mortality, whereas the length of these waves does not. This is in agreement with health literature in suggesting that there is a behavioral risk component involved in mortality associated with high HI. These results indicate that if a heat wave lasts a substantial amount of time, vulnerable individuals can adapt, most likely due to their awareness of the danger or sensitivity to the discomfort caused by the weather. However, if heat waves occur repeatedly, this awareness decreases, causing individuals to engage in less cautious behavior and thus increase their vulnerability to HI-based mortality. The low significance of heat waves with higher danger classifications could be a result of the low number of observations in these categories, or it could be due to the fact that the magnitude of the HI event causes individuals to adjust their behavior accordingly.

Therefore, when examining Hypotheses 2 to 4 we restrict our analysis to the *cross* variables and the variable *nrun_caution*.

Hypothesis 2: HI events affect elderly populations more strongly than young populations

Our second hypothesis proposed that elderly populations are affected more strongly than young populations by high HI events.

Table 3.5 confirm this hypothesis. While both groups are affected negatively by

Table 3.6: Panel GMM regression results for mortality as a dependent variable. Regions are sorted into groups using criteria based on mean GDP per person. Results are shown for each subgroup and variable combination with p-values in brackets.

	Regions with low GDP	Regions with high GDP
n regions	661	693
cross_caution	**3.812e-06 (0.01733 *)**	**7.299e-06 (1.295e-05 ***)**
cross_ext_caution	2.476e-06 (0.2852)	**2.459e-05 (1.59e-05 ***)**
cross_danger	**4.799e-06 (0.005163 ***)**	9.986e-07 (0.7655)
cross_ext_danger	**5.283e-06 (0.01552 *)**	2.475e-05 (0.06467)
nrun_caution	**7.571e-05 (0.0006498 ***)**	**0.0001386 (6.205e-08 ***)**

high HI - disregarding insignificant variables, all influences of HI on mortality are positive - three of five coefficients are large for regions with more elderly populations and we obtain three compared to two significant impacts for those regions.

The difference between the two subgroups of regions is strongest for the number of heat waves that cross the caution level (*nrun_caution*). Younger populations seem to be more robust towards heat waves, especially if the heat is not too high, while older populations seem to be more harmed by longer periods of heat.

With respect to the number of occasions at which heat crosses a certain threshold there is no clear tendency. Heat events in general seem to affect regions with more or less elderly population in a similar way. Hence, hypothesis 2 is only confirmed for the number of heat waves.

Hypothesis 3: HI events affect regions with low GDP per person more strongly than regions with high GDP per person

Our third hypothesis proposed that regions with high GDP per person would be more robust against high HI events than regions with low GDP per person. This hypothesis is not confirmed by our analysis.

As shown in table 3.6, *nrun_caution* has highly significant, positive effects on mortality, regardless of GDP per person. For the *cross* variables we obtain three significant effects for the low GDP regions and only two significant effects for the high GDP regions. However, in most cases the coefficients are higher for the regions with high

GDP.

A closer look at the results for regions with high GDP provides important insights: First of all, it is notable that only measures at danger levels of "caution" and "extreme caution" are significant. HI events above this level have no significant influence on mortality, indicating that at this point, the population takes countermeasures against heat load. This most likely does not take place when the less dangerous thresholds are crossed. Nonetheless, these thresholds are associated with health risks, and these risks take their toll on the population. Thus, although the population is on a whole more robust against high HI, seemingly low-risk HI events are not taken seriously and thus lead to higher mortality. Hubris in the face of nature is not an unfamiliar characteristic of regions with high economic productivity.

Regions with low GDP per person show a different picture. They seem to be more vulnerable to extreme heat levels (crossing the danger threshold), while they seem to be better able to deal with the less extreme heat events. Maybe the measures to deal with extreme heat events are too costly to be a good option for them. The estimates in table 3.6 as well as in table 3.4 show that a higher HI leads to more deaths. Thus, economic development seem to help regions to lower the burden of the more severe high heat events. Since especially these events will become more frequent due to global climate change, we can indeed expect that regions with low GDP are more affected by this.

Hypothesis 4: HI events affect regions with low mean HI more strongly than regions with high mean HI

Our fourth hypothesis proposed that regions with high mean HI are less strongly affected by HI events than regions with low mean HI. Intriguingly, we find the opposite, as shown in table 3.7.

Regions with low mean HI exhibited highly significant relationships between only one HI variable and mortality, whereas two HI variables were highly significant in the case of regions with high mean HI. In the case of regions with high mean HI, both of these variables are associated with the "caution" danger level. The fact that none of the variables associated with higher danger levels is significantly associated with

Table 3.7: Panel GMM regression results for mortality as a dependent variable. Regions are sorted into groups using criteria based on mean heat index. Results are shown for each subgroup and variable combination with p-values in brackets.

	Regions with low mean heat index	Regions with high mean heat index
n regions	607	447
cross_caution	***-1.189e-05 (0.000167 ***)***	**6.283e-06 (5.868e-05 ***)**
cross_ext_caution	4.922e-05 (0.4112)	-1.572e-06 (0.4851)
cross_danger	-0.02235 (0.119)	-5.769e-07 (0.733)
cross_ext_danger	0.0001019 (0.373)	-5.094e-07 (0.8131)
nrun_caution	7.616e-05 (0.3147)	**8.905e-05 (6.638e-06 ***)**

mortality suggests that the populations of regions with high mean HI do indeed take countermeasures against heat load when extreme HI events occur. This is apparently not the case with less dangerous HI events, which nonetheless can measurably affect regional mortality. While the heat countermeasures do seem to be effective, they are likely adopted too late, at the cost of lives at the caution level.

In contrast, regions with low mean HI are fascinatingly unique among all region groups. The typically significant variables are insignificant for these regions and if they are significant (*cross_caution*) the effect has the opposite sign than usual. That means that if HI crosses the caution threshold mortality decreases. Several things can be noted here. This indicates not only the absence of common mechanisms often observed in other regions – for example, that the number of heat waves at the "caution" level is not an issue in these regions – but also that the significant variables affect the population in ways that do not occur in other groups. It is probable that due to the low frequency of high HI events, the population is more acutely aware of their dangers and reacts especially strongly accordingly. It might also be that in regions that are usually very cold, mortality is more driven by cold than by hot periods and that a higher number of heat events in a year comes together with a lower number of extremely cold days.

Conclusions

This paper investigated the effects of heat on mortality, using a range of metrics to capture the interactions between heat events, measured using heat index, and mortality on a regional level in Europe. Using panel GMM analyses, a variety of mechanisms could be observed through which high HI influences mortality. In general, high HI events were shown to have significant, positive relationships with regional mortality, although the mechanisms at play in each group, as well as the effects they expressed, differed meaningfully.

Across all groups, the most important variables were the number of heat waves at the "caution" level (*nrun_caution*) and the number of days on which the maximum HI exceeded the "caution" level (*cross_caution*). The length of heat waves has been found to be less important.

The different effects of HI measures on mortality across groups of regions provided important insights into these interactions. Although it was shown that the frequency of high HI events is relevant due to their consistent effect of increasing mortality, the other mechanisms, such as the population's response to hot weather, are able to effectively counterbalance these influences, which was found to be the case, e.g. for extreme heat in high GDP regions. Awareness seems to be key to safely mitigating mortality caused by hot weather.

Heat events have been observed to increase in frequency and intensity in Europe since 1979 Lee and Brenner [2015]. It can be expected that this trend will continue in the course of climate change. As hot weather increases mortality, it is a straightforward assumption that this will be associated with higher economic costs and negative consequences for longevity. This is exacerbated by the increasing elderliness of Europe's population, as the paper demonstrates that elderly populations are more vulnerable to heat events. Furthermore, low GDP regions seem to be especially hurt by the expected increase in dangerous heat event. Countermeasures can be taken to mitigate the effects of heat, but these cost money, either through increased expenditures or decreased productivity.

Strategies for mitigating heat are clearly important and have been shown in this and other studies to effectively decrease the health consequences of hot weather. This indicates that much can be learned from regions that deal well with hot weather. Applying these lessons in other places could save lives and improve quality of life. Investigating these mechanisms and exploring strategies for transferring them to other places is a worthwhile pursuit that should yield important results for regions in the future.

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Appendix

Regression results

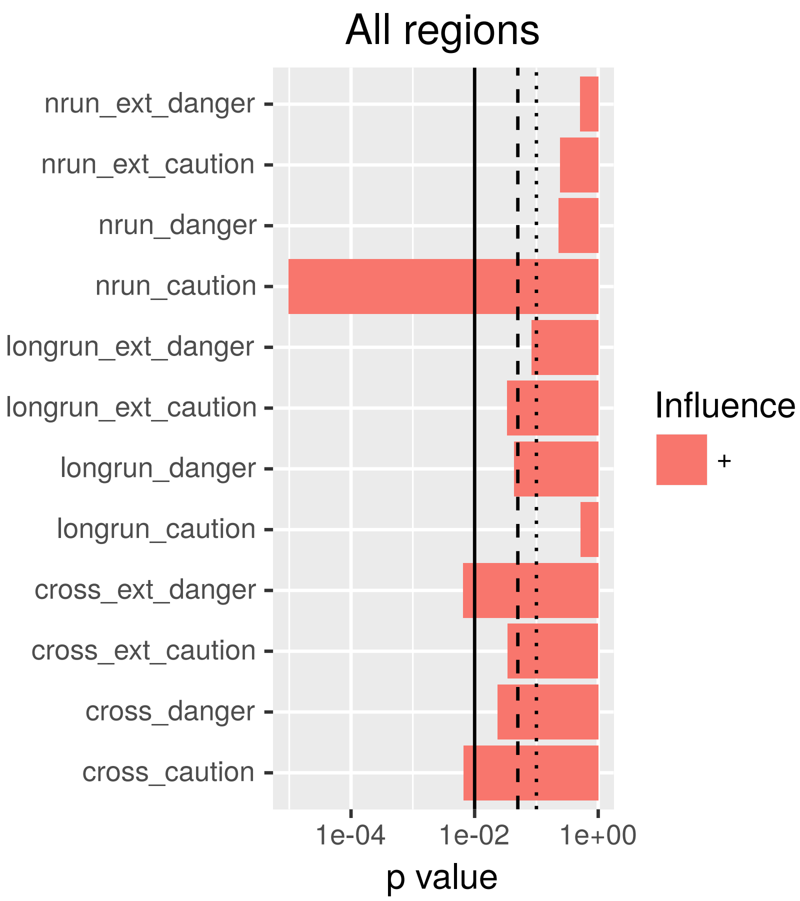

Figure 3..2: Influence of HI on mortality in all regions. P-values are shown on a logarithmic scale on the x-axis. Farther left shows higher significance; lines denote standard significance levels (0.1, 0.05, 0.01). The coefficient's sign is denoted by each bar's color.

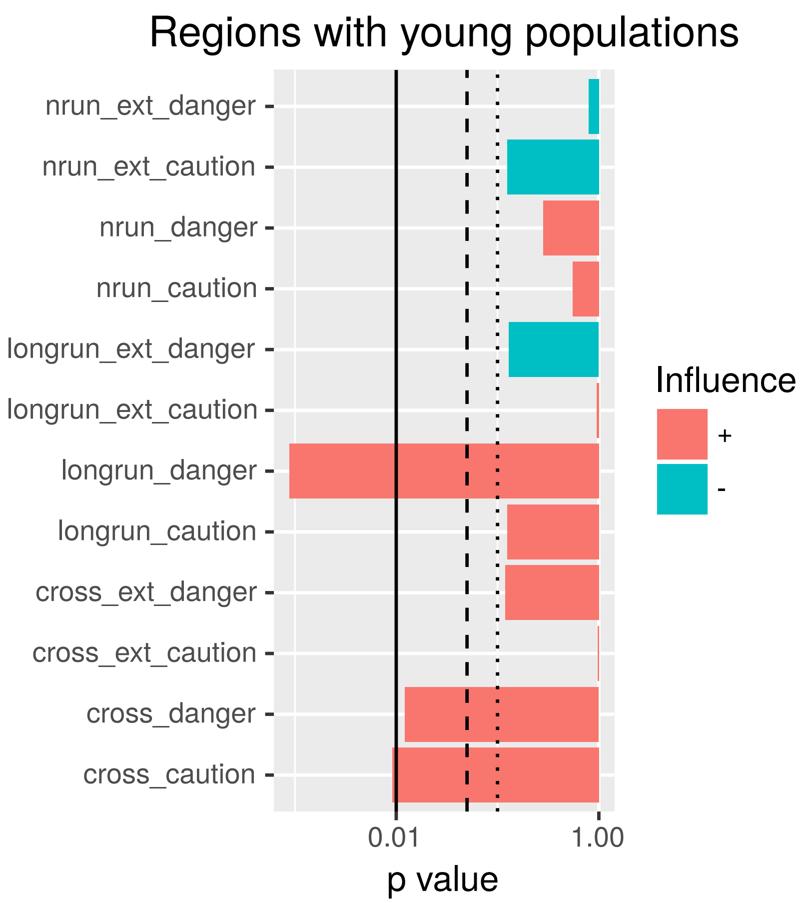

Figure 3..3: Influence of HI on mortality in regions with young populations. P-values are shown on a logarithmic scale on the x-axis. Farther left shows higher significance; lines denote standard significance levels (0.1, 0.05, 0.01). The coefficient's sign is denoted by each bar's color.

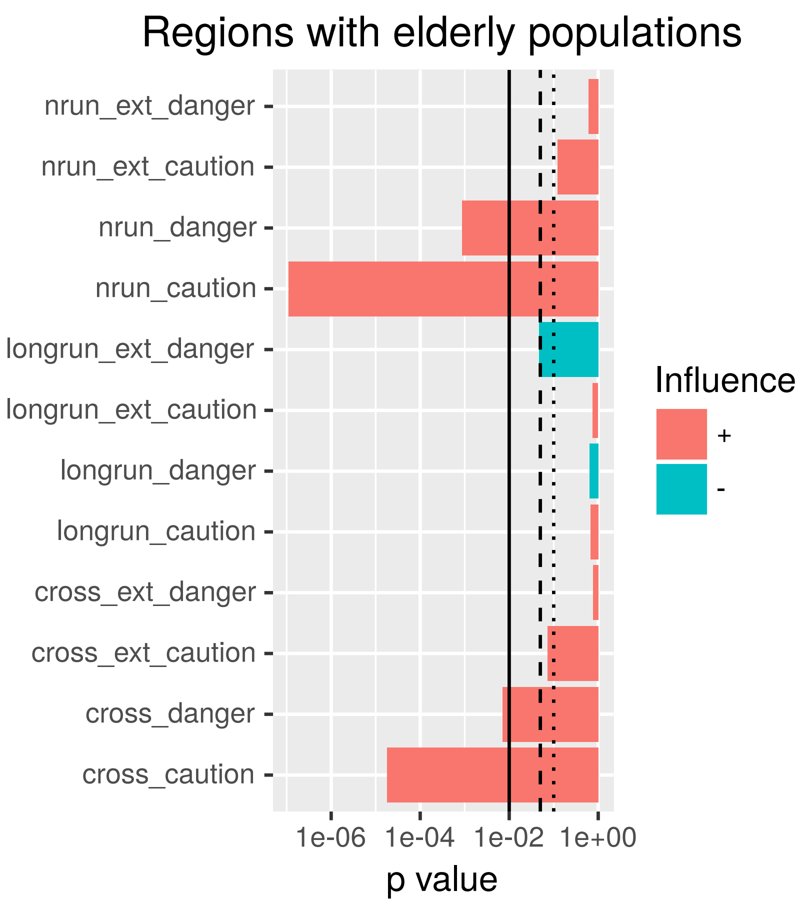

Figure 3..4: Influence of HI on mortality in regions with elderly populations. P-values are shown on a logarithmic scale on the x-axis. Farther left shows higher significance; lines denote standard significance levels (0.1, 0.05, 0.01). The coefficient's sign is denoted by each bar's color.

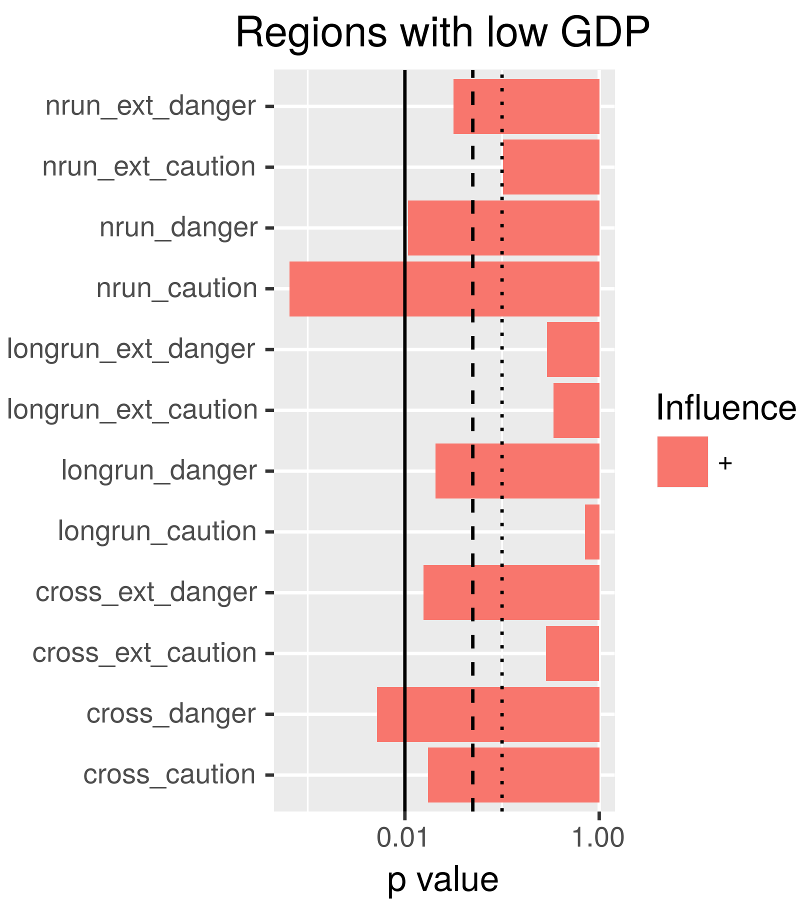

Figure 3..5: Influence of HI on mortality in regions with low GDP per person. P-values are shown on a logarithmic scale on the x-axis. Farther left shows higher significance; lines denote standard significance levels (0.1, 0.05, 0.01). The coefficient's sign is denoted by each bar's color.

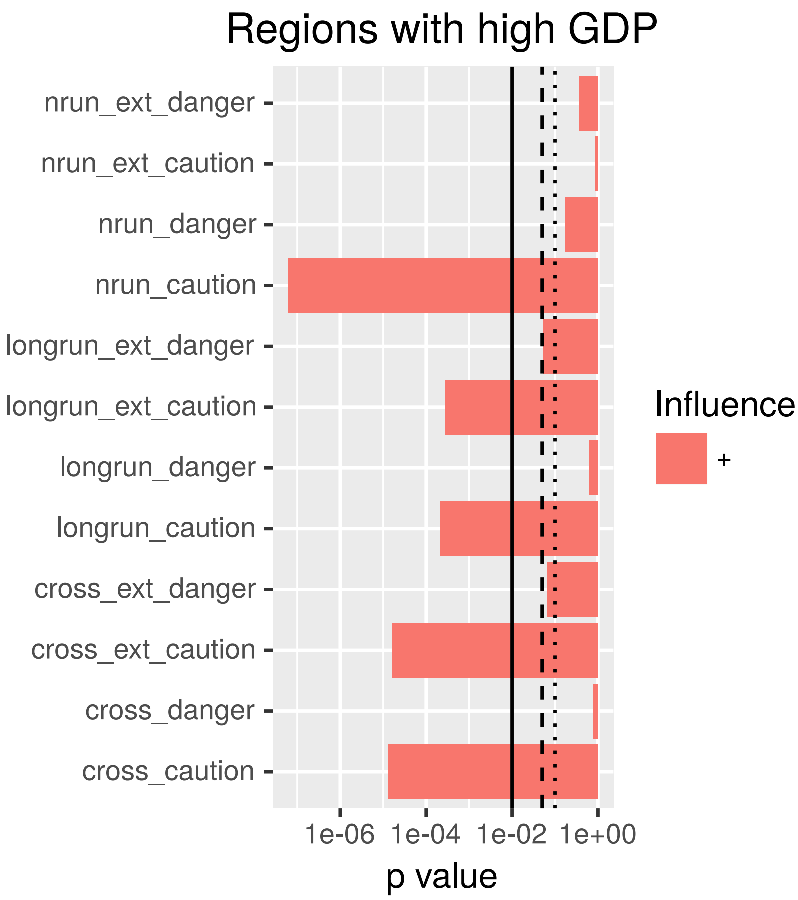

Figure 3..6: Influence of HI on mortality in regions with high GDP per person. P-values are shown on a logarithmic scale on the x-axis. Farther left shows higher significance; lines denote standard significance levels (0.1, 0.05, 0.01). The coefficient's sign is denoted by each bar's color.

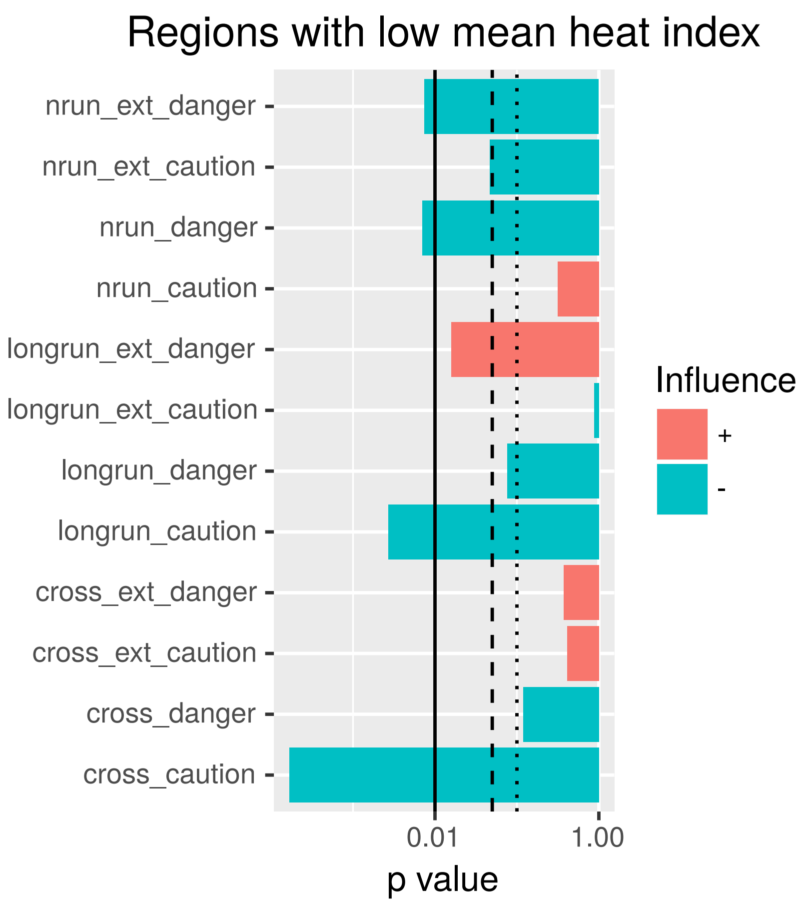

Figure 3..7: Influence of HI on mortality in regions with low mean HI. P-values are shown on a logarithmic scale on the x-axis. Farther left shows higher significance; lines denote standard significance levels (0.1, 0.05, 0.01). The coefficient's sign is denoted by each bar's color.

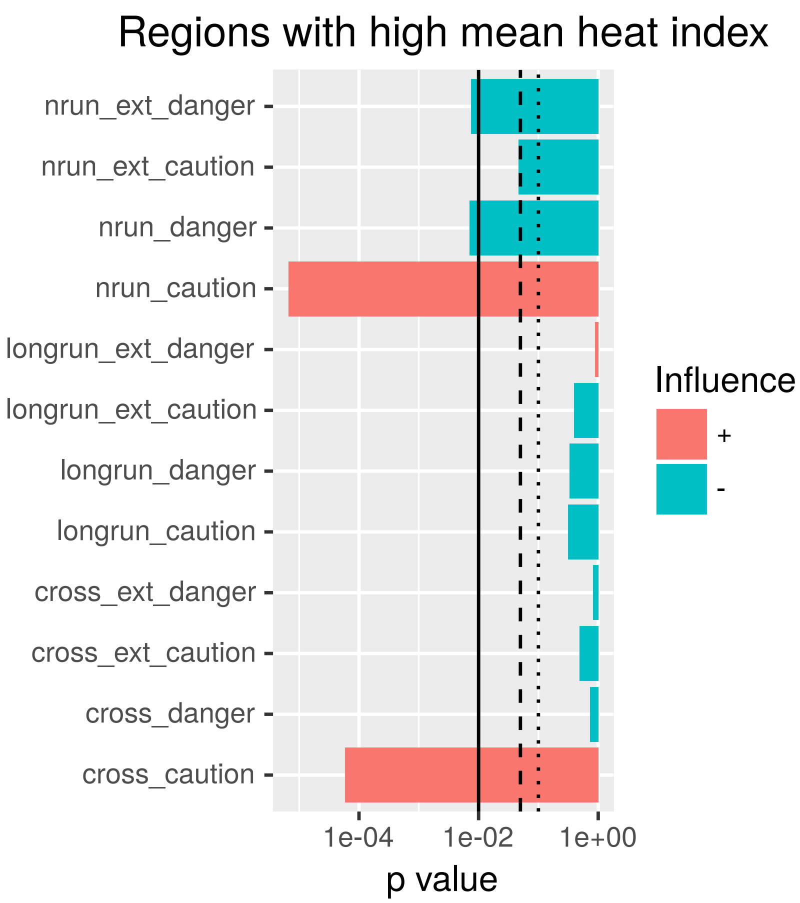

Figure 3..8: Influence of HI on mortality in regions with high mean HI. P-values are shown on a logarithmic scale on the x-axis. Farther left shows higher significance; lines denote standard significance levels (0.1, 0.05, 0.01). The coefficient's sign is denoted by each bar's color.

Chapter 4

Influence of heat index on economic growth: Is productivity hampered by climate change?

Submitted to Environment and Development Economics

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Introduction

The last decades were the warmest in the last half millennium [Luterbacher et al., 2004]. Climate change researchers predict further changes in global temperatures for the foreseeable future [Intergovernmental Panel on Climate Change, 2014]. While climate change and its general impacts are discussed extensively in the literature, its economic impacts are mainly studied using theoretical models [e.g., Bosetti et al., 2008, Eboli et al., 2010, Bosello et al., 2012]. Empirical studies of the impact of climate on economic growth focus on the effects of single, climatologically extreme events [e.g., Skidmore and Toya, 2002, Toya and Skidmore, 2007, Noy, 2009, Thanasis Stengos, 2012, Loayza et al., 2012, Strobl, 2012, Fomby et al., 2013].

The impact of weather on economic growth has already been demonstrated in the literature. For example, Barrios et al. [2010] showed that rainfall is an important determinand of growth in African countries. Such meteorological determinands are not restricted to precipitation. For example, heat can reduce worker productivity by forcing workers to work more slowly and take more breaks [Kjellstrom et al., 2009]. Heat can also hamper growth by directly causing health problems [Poumadère et al., 2005], preventing people from working and diverting resources to health care. Unhealthy and dangerous heat events are projected to increase in frequency and intensity in the future [Beniston, 2004, Intergovernmental Panel on Climate Change, 2014]. However, the spatial distribution of this intensitifed heat will be uneven across the globe [e.g., Vose et al., 2005, Diffenbaugh and Ashfaq, 2010, Diffenbaugh and Scherer, 2011, Alexander and Arblaster, 2009, Meehl et al., 2009, Smith et al., 2005, Sherwood et al., 2008].

This paper adds to the existing literature by studying the impact of heat and precipitation on economic growth in 105 countries over a 19-year period. To our knowledge, it is the first study that analyses the impact of changes in yearly average heat and precipitation on economic growth for many countries. While climate change causes both an increasing frequency of single, climatologically extreme events and a change in average conditions, such as temperature and precipitation, the empirical literature has so far focused on the economic effects of extreme events. Our knowledge about the economic effects of changes in the average climatological conditions is scarce so far. For example, how much is the overall economy in Spain hurt if the average temperature increases by 4 degrees?

In contrast to climatologically extreme events, the continuous changes in average climatological conditions do not cause visible damages. Instead, we expect slight changes in productivity due to the effects on humans outlined above. In order to detect these changes in productivity, the relationship between climatological conditions and economic growth is studied with yearly data in this paper. Understanding this relationship makes it possible to estimate the cumulative loss in economic growth due to climate changes. Hence, this paper provides first empirical insights into the long-term effects of cumulative climate change over time, thus complementing studies on the immediate impacts of extreme climate events.

We use the heat index (HI) [Anderson et al., 2013], a physiologically relevant measure of heat load on the human body that is commonly used in the health and meteorological communities to evaluate the effects of heat on humans, and yearly precipitation. A GMM panel regression is applied, with countries partitioned into different groups according to baseline economic and climatological factors. The study's scale sets it in a unique position to contribute to existing literature, which focuses on individual case studies [e.g. Burkart et al., 2011, Basara et al., 2010], by offering a perspective that provides insight on a country level across the entire globe and over an extended period of time (19 years). We find that, on average, high HI has a negative, precipitation a positive impact on economic growth. We also find clear differences between the subgroups of countries.

Theoretical background

The influence of weather on economic activity

Weather influences economic activity using several mechanisms. Some of them are straightforward. For example, agricultural productivity is strongly dependent on weather conditions. In dry areas - especially in developing countries - precipitation can be a limiting factor in plant growth, so that low precipitation can greatly reduce the output of the agricultural sector [e.g. Barrios et al., 2010]. Drought, especially combined with heat stress, represents a danger to agricultural productivity and the availability of food worldwide [Lipiec et al., 2013].

Studies have shown that the potential of some weather variables - particularly heat - to reduce agricultural productivity have been underestimated in the past [e.g. Barlow et al., 2015]. Therefore we can deduce that the nonlinear effects of increased heat and decreased precipitation in the course of climate change will have greater impacts on the global economy as have been estimated thus far, especially as these effects propagate through the economy. Although high temperatures can be beneficial to crop growth [Yin et al., 2016], too much heat is always detrimental to crops.

The mechanisms by which crop growth is hindered by heat are in part an ecological question. Plants lose moisture more quickly due to heat, and cellular activity can deteriorate when exposed to excessively high temperatures. These effects are dependent on manifold environmental factors, including the type of plant involved [Edreira and Otegui, 2012]. Thus the uneven distribution of crops and increases in temperature in the course of climate change must be accounted for when evaluating specifically the effects of higher temperatures on agricultural productivity [Teixeira et al., 2013]. Beyond this, the change in the distribution of pests and pathogens which can harm crops - and their ability to establish a long-term presence in new areas - will affect the agricultural sector as a result of climate change in the years to come [Bebber, 2015].

The effects of weather on agriculture are intuitive and fairly straightforward, but agriculture is by no means the only sector to be significantly influenced by weather. For example, hot weather greatly increases energy usage through increased use of ventilation and air conditioning [Wang et al., 2012]. Despite numerous studies confirming the intuitive assumption that higher temperatures lead to greater energy consumption due to cooling, past estimates of these costs are likely in need of revision, as newer methodologies and data have become available [Kaufmann et al., 2013]. The fact that higher temperatures will lead to higher heating costs, taking away available capital for other investments is clear nonetheless.

The energy sector is also strongly affected by heat and precipitation. Over 80% of global power production is from thermoelectric sources [Edenhofer et al., 2011], which require the use of water as a coolant [Förster and Lilliestam, 2009]. Warmer weather leads to higher temperatures in coolant water, which lowers the power plants' cooling efficiency. This lowered efficiency, which is often exacerbated by a water scarcity accompanying the hot weather, has been shown to generate high costs for the energy sector already, and it can be expected that this trend will continue in the future [Förster and Lilliestam, 2010]. Crucially, this mechanism is not only a function of temperature, but also of the duration and frequency of high temperature events [Eisenack, 2016].

The macroeconomic effects of higher energy prices - often studied in the context of oil prices - have been well demonstrated in the literature [e.g. Kilian and Vigfusson, 2011, Kilian, 2008], showing that the increasing effect of weather on energy costs will surely play a significant role in determining economic growth in the course of climate change.

Weather conditions also affect human health through a variety of mechanisms. The interactions between weather and human health are complex and global climate change can be expected to have both positive and negative effects on health. However, the overall effect of climate change can be expected to be negative, particularly due to excessive heat [Haines et al., 2006]. The effects of heat differ depending on various socioeconomic factors [Tan et al., 2007, Conti et al., 2005]. This produces a heterogeneous pattern of health detriment in the course of climate change [Kovats and Hajat, 2008]. Mitigation is possible, but involves a broad cross-section of disciplines encompassing e.g. improvements to housing, awareness campaigns and better urban planning [Gosling et al., 2009]. The tangible, economic consequences of climate change are thus as heterogeneous as their mechanisms are diverse, ranging from direct costs in health care to loss in economic productivity as a consequence of mortality and including lowered productivity among the healthy population due to the necessity of more frequent breaks, etc. [Bosello et al., 2006].

The mechanisms listed above are highlighted specifically in order to show that climate change will affect economic growth worldwide in concrete ways. While all sectors of the economy are influenced by climate change, some sectors are especially influenced due to specific mechanisms. Additionally, we can expect that the increased or decreased growth in a given sector will also affect up- and downstream sectors, so that the effects of changes in weather patterns will propagate throughout economies. The short-term effects of single extreme events can usually be compensated in the medium-run. Due to the long-term nature of climate change, however, the negative effects of climate change will be compounded as it continues over extended periods of time. They will be further potentiated by interactions between sectors, becoming a long-term problem, especially for more vulnerable economies. The more developed a country is, the better it is able to compensate the negative effects of climate change, because it possesses the necessary budget and technological knowledge to conduct respective policy measures [Gosling et al., 2009].

According to the mechanisms outlined above, low precipitation and heat lower the economic output of a country. However, the effects of these two weather variables are nonlinear and independent of each other. In some cases, the influence of a given variable can even switch signs when certain thresholds are reached. For example, dry areas might be positively influenced by precipitation because it allows crops to grow more than they would otherwise. In other cases, excessive amounts of precipitation might lead to flooding, causing damages not only to crops but also to infrastructure and potentially costing human lives. It could also be argued that heat affects regions differently – regions where the population has ample access to shade, air conditioning, water, etc. might react much more robustly to high heat loads in comparison with other areas. Countries with typically low temperatures might even benefit from temperature increases. Additionally, the expected climate could influence the population's preparedness to adapt to heat and precipitation events, i.e. populations which often have little precipitation or high heat could react more robustly to extreme events because the population is informed of possibilities to mitigate the effects of heat and prepared to put these into effect. Therefore, we hypothesize:

1. Countries which normally receive large amounts of precipitation will display a negligible or negative relationship between precipitation and growth, while countries that normally receive little precipitation will have a positive relationship between precipitation and growth.

2. Countries will show a strong negative relationship between heat events and growth. This effect will be stronger for countries where the temperature is normally average or low.

3. The relationship between weather and growth will be less pronounced in more developed countries than in less developed countries.

Economic growth model

Modelling economic growth is usually based on the assumption of a Cobb-Douglas production function. In the context of endogenous growth theory [Romer, 1986, Lucas, 1988, Romer, 1990, Aghion and Howitt, 1992] a specific role has been attributed to human capital and technological advancement. We follow the usual approach [Mankiw et al., 1992] using the equation

$$Y_{it} = K_{it}^{\alpha} H_{it}^{\beta} \left(A_{it} L_{it}\right)^{1-\alpha-\beta} \tag{4.1}$$

where Y signifies economic output, A technology, H human capital, K capital and L labor.

We add the effects of weather conditions to the usual resulting growth equation. Due to the lack of adequate data we do not consider technological advancement explicitly. Hence, the growth equation reads:

$$\Delta ln\left(\frac{Y_{it}}{P_{it}}\right) = \delta \cdot ln\left(\frac{Y_{it}}{P_{it}}\right) + \alpha \cdot \Delta ln\left(\frac{C_{it}}{P_{it}}\right) + \gamma \cdot \Delta ln(H_{it}) + \beta \cdot \Delta ln\left(\frac{L_{it}}{P_{it}}\right) + \sum \delta_j \cdot W_{j,it} \tag{4.2}$$

where P_{it} denotes the size of the population in question, Δ denotes the difference between timestep $t+1$ and t, and the weather is denoted by the variable W, with $W_{1,it}$ standing for the mean daily precipitation and $W_{2,it}$ for a particular heat index event (see section 4). For a similar approach see e.g. [Wang, 2009]. As described above, the influence of weather conditions on the economic activity in a country can be seen as changing the productivity of the economy. Equation 4.2 implements this assumption: Including the weather variables in a standard growth equation with the usual growth determinands implies that the impact of the weather variables on the total factor productivity is measured.

Material and methods

Data

Physiologically, temperature is a poor metric for measuring heat load in humans, because the actual load consists of the combination of latent and sensible heat. Latent heat can be dispersed from the body through the evaporation of perspiration. This process becomes less efficient dependent upon several factors above and beyond the absolute temperature - e.g. wind speed, radiation, humidity, etc. As wet bulb globe temperature (WBGT) takes these modifying conditions into account [International Organization for Standardization, 2010], it is often used to measure physiological heat load when the necessary data is available.

However, WBGT is impractical outside of controlled environments because so many variables are needed to compute it, all of which vary widely on short spatial scales. This has led to the prevalence of the heat index (HI) for most heat load assessments outside of extremely small, controlled environments [e.g., Anderson et al., 2013, Perry et al., 2011, Kysely and Kim, 2009, El Morjani et al., 2007, Burkart et al., 2011, Basara et al., 2010]. Heat index can be computed using only two variables - temperature and humidity - both of which are readily available in standardized weather observations and weather models. HI was taken from a global HI data set, which was derived from ERA-Interim [Lee and Brenner, 2015]. This data is available as daily minima, means and maxima for each grid point.

Precipitation data was also gained from the ERA-Interim Reanalysis [Berrisford et al., 2009] by summing the daily convective and large-scale precipitation from each analysis of each day.

Next, the data was aggregated to usable levels using GRASS GIS [GRASS Development Team, 2015]. In the case of precipitation, this was done by aggregating to single yearly values. In the case of HI multiple effects need to be accounted for when creating yearly metrics. On the one hand, crossing danger thresholds could in and of itself damage productivity and thus growth in a given year. On the other hand, single hot days might have only trivial effects because they could be compensated well, as opposed to long heat waves. For this reason, we aggregated the HI data first by counting the number of hot days, and second by computing the length of the longest contiguous heat wave in each year. We tested both the number of hot days and the length of heat waves as variables for representing heat in the regression analysis. The length of heat waves provided more significant results and the number of hot days did not bear any additional information, so that we restricted our analysis to the inclusion of the length of heat waves.

Hot days were defined as those where the HI exceeded the "caution" level as outlined in the United States National Weather Service (NWS) heat safety guidelines [National Weather Service, 2014]. Both the mean daily HI and the daily maximum HI were used, because both the daily maximum as well as the HI distributed throughout the day could be of relevance.

The global data for precipitation and HI was then spatially aggregated to population-weighted means for each country and each year. Gridded population data from the Global Rural-Urban Mapping Project [Center for International Earth Science Information Network - CIESIN - Columbia University; International Food Policy Research Institute - IFPRI; The World Bank; Centro Internacional de Agricultura Tropical - CIAT, 2011] was used to create the weighting grid for each country.

Economic data from 105 countries, excluding oil exporting nations as is usual in the literature [Bond et al., 2010], for the years 1991–2009 were analyzed using data from the Penn World Table [Robert C. Feenstra, Robert Inklaar, Marcel Timmer, 2013]. The output side real GDP at current PPP was used as Y, the capital stock at current PPPs as K. The number of persons employed in each country was used as a proxy for labor input L. An index that approximates human capital per person based on years of education and returns to education (given in the Penn World Table) was used as H. Population was used as P.

Regression approach

As is common in the empirical economic growth literature, a panel GMM regression was used, which allows testing for causality through the use of instrument variables

Table 4.1: Data subsets partitioned by mean GDP per capita, by mean annual HI and mean monthly precipitation.

Countries with	$\leq$ \$6400 mean GDP per person	$>$ \$6400 mean GDP per person
Low heat	HI ≤ 70	HI ≤ 46
High heat	HI > 70	HI > 46
Low precipitation	≤ 0.003	≤ 0.0021
High precipitation	> 0.003	> 0.0021

[e.g., Hasan and Tucci, 2010, Vu et al., 2012, Museru et al., 2014]. Following this practice, we used lagged variables and export and import rates as instruments. Time and country fixed effects were included in the estimations.

In our study, we analyse the idiosyncratic effects, which are stated in our hypotheses, by partitioning the data into different groups, using both climatatological and economic criteria. To this end, we apply the regression approach to eight different subsets of our data as given in table 4.1. The partitioning is done such that nearly the same number of countries is found in each subset. Therefore, the thresholds distinguishing between low and high heat and between low and high precipitation countries are different for high GDP and low GDP countries. In total we conduct 16 panel regressions because for each subset the heat variable refers once to the mean daily HI and once to the maximum daily HI.

Results and discussion

The first interesting result relates to the kind of heat variable that is used. Originally, we tested two approaches: Counting the number of days in a year in which the heat index exceeds the caution level and counting the number of days of the longest heat wave (successive days in which the heat index exceeds the caution level) within a year. Using the length of heat waves leads to many more significant results for this variable in the 16 panel regression than using the total number of heat days. Longer heat waves seem to matter much more for the economy than disparate heat events. This confirms our assumption that it is not sufficient to look at single extreme events. Economies seem to be usually able to compensate such single events, while they are not able to compensate longer periods of heat. We also checked the impact of extreme heat events, using higher thresholds for the heat level, and the results confirm the above results: It is not the strength of the heat event that matters but its duration.

Therefore, we restrict the further analysis to the result for the heat variable that is based on the number of days of the longest heat wave per year. The complete regression results for all 16 panel regressions are provided in the appendix. In the following subsections the results that relate to our three hypotheses are discussed.

For the other variables included in our analysis we find results that are common in the literature. Previous GDP always has a negative impact, so that we find convergence towards the steady state. Capital investments always have a positive impact, which is significant in all regressions except one. Labor inputs have a positive impact in most cases in the more developed countries. Human capital is rarely found to have a significant impact, but if this is the case the impact is positive. Interestingly, significant positive impacts are only found for high precipitation-high GDP countries and for high heat-low GDP countries. We have no straightforward explanation for this.

Hypothesis 1: Impact of precipitation

Table 4.2 presents the results (estimate and p-value only for total precipitation) for the dependence of economic growth on total precipitation. It can be easily observed that the results only slightly depend on whether heat is measured by daily means or daily maxima and whether we consider more or less developed countries. We obtain a clear robust picture: There is a significantly positive effect of precipitation on economic growth in countries with low average precipitation or low HI values. All significant estimates range between 20 and 37, meaning that an increase by 20 mm precipitation per year leads to an increase in the growth rate of 0.03–0.05%.

No significant results are found for countries with high average precipitation or for countries with high HI values. Although the differences are not very strong, the positive effect becomes insignificant for less developed countries if the daily mean of the heat index is used. Overall, the results are slightly less significant using the daily mean.

Table 4.2: Estimates of coefficients explaining change in logged annual growth in per-person output-side GDP in millions of 1995 USD per mm yearly precipitation. Corresponding p-values are shown in brackets.

	$\phi Y_{it}/P_{it} \leq 6400$		$\phi Y_{it}/P_{it} > 6400$	
	with mean HI	with maximum HI	with mean HI	with maximum HI
Low precipitation	**20.903 (0.0762 .)**	**25.5510 (0.0428 *)**	**36.9380 (0.0173 *)**	**36.9643 (0.0409 *)**
High precipitation	4.0196 (0.8016)	5.9859 (0.6904)	10.9080 (0.1290)	6.0881 (0.2667)
Low heat	**20.668 (0.0667 .)**	**23.7068 (0.0280 *)**	**20.3075 (0.0056 **)**	**24.018 (0.0066 **)**
High heat	2.262 (0.909)	2.2972 (0.9064)	14.0762 (0.1888)	10.9411 (0.2798)

Our results are in line with the first hypothesis outlined in section 4. In countries with low average precipitation the economy grows more in years with higher precipitation, probably due to better agricultural conditions, and grows less in years with lower precipitation, probably because of resulting droughts. The same result is found for countries with a low average HI. The very similar results for countries with low precipitation and low heat make it very likely that this result is obtained due to a large overlap between the two subsets. The insignificant results for countries with high average precipitation indicate that excessive amounts of precipitation within a year do not cause detectable problems – given our approach – for the economy. Of course, this must not be confused with the effects of short-term extreme precipitation events leading to floods.

Hypothesis 2: Impact of heat

Table 4.3 presents the results (estimate and p-value only for the heat wave length) for the dependence of economic growth on heat wave length. The table clearly shows that this impact depends on the sample of countries that is studied. We obtain three cases with significant, negative effects of heat waves on economic growth. This confirms the first part of hypothesis 2: Heat waves have a negative impact on economic growth. The significant estimates range between 0.0006 and 0.0008, meaning that prolonging heat waves by one day causes a reduction of economic growth by approximately 0.07%. A

Table 4.3: Estimates of coefficients explaining change in logged annual growth in per-person output-side GDP in millions of 1995 USD per day in longest heat wave of the year, measured based on daily mean and maximum HI. Corresponding p-values are shown in brackets.

	$\phi Y_{it}/P_{it} \leq 6400$		$\phi Y_{it}/P_{it} > 6400$	
	with mean HI	with maximum HI	with mean HI	with maximum HI
Low precipitation	0.0003 (0.1764)	0.0000 (0.0939)	0.0002 (0.6720)	**-0.0008 (0.0096 **)**
High precipitation	-0.0000 (0.8198)	0.0001 (0.7169)	**-0.0006 (0.0008 ***)**	0.0001 (0.4247)
Low heat	0.0001 (0.9091)	0.0004 (0.0943 .)	-0.0021 (0.293)	-0.0001 (0.5916)
High heat	-0.0000 (0.8859)	-0.0001 (0.3502)	**-0.0006 (0.0046 **)**	0.0002 (0.2505)

straightforward linear regression shows that an increase in HI by 1 °leads to an increase in the length of the longest heat wave of almost 2 days. Therefore, assuming a constant distribution of humidity and a uniform global increase in temperature of 2–4 °C, one could expect losses in economic growth of approximately 0.46–0.91%. However, the second part of hypothesis 2 is not confirmed. Dividing the sample according to the average HI values leads to a significant result for the high heat countries but no significant result for the low heat countries.

The fact that cool countries were less affected by high HI than expected could have several reasons. Events with high HI could be very rare and short, so that the effect is insignificant. In this case the data is simply not sufficient to make a statement. Alternatively, years with higher temperatures might mean in cooler countries less burden by cold days and more burden by hot days, which might counter-balance each other.

Whether a country is characterised by low or high average precipitation seems to play no role for the impact of heat on economic growth. We find significant results for both country samples. We are also not able to make a final statement about whether heat waves considering mean or maximum daily heat are more important. Significant results are obtained one time for the maximum and two times for the mean daily HI value. However, one might interpret the results to indicate that in humid countries, high HI distributed throughout the day has a greater impact, whereas in dry countries a high peak heat event is more damaging. Another factor could be the availability of water; as proper hydration can play a crucial role in the body's ability to cope with high heat load, people in dry countries may have be negatively impacted by a high peak HI, while people in humid countries can compensate for these peaks by drinking more water, bathing more frequently, etc.

Hypothesis 3: More vs. less developed countries

Partitioning the sample by GDP per capita did not return results in agreement with the third hypothesis. The length of the longest heat wave in which the mean temperature exceeded the caution level had a significant, negative impact on economic growth in developed countries with high average HI, low average precipitation and high average precipitation. No such significant impact was found for less developed countries.

In contrast, concerning the effects of precipitation, similar effects were found for countries with low and high GDP per capita. However, the effects are less significant for the countries with low GDP per capita. Hence, we find a contradiction to the third hypothesis: More developed countries are more affected by weather conditions, especially by heat.

The lack of significant effects of HI on economic growth in developing countries could indicate that less developed countries employ more effective strategies for dealing with high HI, for example by extending work times into cooler evening hours or taking more breaks. It could also show that people in less developed countries are more accustomed to working under unfavorable conditions. Another explanation could be that high HI affects the elderly most acutely, and developed countries generally have a higher elderly proportion of the population. The findings could also point to the fact that HI has a very small – nearly negligible – effect on economic growth in developing countries compared to other more decisive variables. Another possible explanation is the lower quality of data because of higher difficulties involved in collecting economic data in developing countries. Further investigation would be needed to understand this relationship more clearly.

Conclusions

This paper examines the effects of precipitation and heat index on economic growth. It was found that precipitation has a significant, positive effect on economic growth in dry countries. This holds for developing and developed countries. High HI was shown to have a significant, negative effect on economic growth in developed countries, while no effect was found for developing countries. From theoretical considerations such an effect was rather expected for developing countries. Several potential explanations for this finding are discussed above. One potential reason for the missing significant results for developing countries is the quality of the data and the fact that data was aggregated to the country level, rather than physically defined spatial units. More detailed regional data might provide further insights and further investigateing this issue would be a valuable endeavor for future studies.

However, the examination in this paper provides first findings on the consequences of climate change on the growth of economies. The distribution of moisture and heat changes in the course of climate change. According to our results, it can be expected that especially developed countries will suffer from reduced economic growth if heat increases. Our estimation suggests that the predicted increase of temperatures by 2 to 4 degrees will lead to a loss of economic growth by approximately 0.5–1%.

Our study provides a first estimation of the effects of some climatological changes in the course of the expected climate change. This estimation is based on data on the country level and holds for the average country. Countries and also regions will differ in their ability to compensate such effects. Hence, understanding the mechanisms behind the phenomenon in more detail and studies on the regional will help to react to the expected climate changes and reduce the negative effects on economic growth. This paper presents a first analysis in this direction. Further studies will hopefully follow.

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Appendix

Regression tables

Table 4..4: Panel GMM regression results for groups of countries partitioned by mean yearly per-person GDP and mean daily HI. The numbers shown are estimates for coefficients explaining annual changes in logged, per-person output-side GDP, capital, labor and human capital measured in millions of 1995 USD as determined by the number of days in the longest heat wave of the year, whereas the longest heat wave is characterized by contiguous days in which the mean daily HI exceeded the caution level. Corresponding p-values are shown in brackets. For further info concerning the determinands, see [Robert C. Feenstra, Robert Inklaar, Marcel Timmer, 2013]).

Variable	$\phi Y_{it}/P_{it} \leq 6400$ HI ≤ 70	$\phi Y_{it}/P_{it} \leq 6400$ HI > 70	$\phi Y_{it}/P_{it} > 6400$ HI ≤ 46	$\phi Y_{it}/P_{it} > 6400$ HI > 46
Observations	468	486	450	450
Countries	26	27	25	25
$ln\left(\frac{Y_{it}}{P_{it}}\right)$	**-0.1373** **(0.0409 *)**	**-0.2047** **(0.007 **)**	**-0.1545** **(0.0004 ***)**	**-0.2371** **(0.0000 ***)**
$ln\left(\frac{C_{it}}{P_{it}}\right)$	**4.314** **(0.0029 **)**	**0.4525** **(0.0000 ***)**	**0.1956** **(0.0026 **)**	**0.6028** **(0.0001 ***)**
$ln\left(\frac{L_{it}}{P_{it}}\right)$	-0.0632 (0.6539)	0.019 (0.8998)	**0.469** **(0.0002 ***)**	0.0863 (0.5010)
$ln\left(\frac{H_{it}}{P_{it}}\right)$	0.7359 (0.5627)	**10.8291** **(0.0200 *)**	0.4409 (0.4585)	0.5404 (0.6646)
Precipitation	20.668 (0.0667 .)	2.262 (0.909)	**20.3075** **(0.0056 **)**	14.0762 (0.1888)
Heat wave length	0.0001 (0.9091)	-0.0000 (0.8859)	-0.0021 (0.293)	**-0.0006** **(0.0046 **)**

Table 4..5: Panel GMM regression results for groups of countries partitioned by mean yearly per-person GDP and mean daily precipitation. The numbers shown are estimates for coefficients explaining annual changes in logged, per-person output-side GDP, capital, labor and human capital measured in millions of 1995 USD as determined by the number of days in the longest heat wave of the year, whereas the longest heat wave is characterized by contiguous days in which the mean daily HI exceeded the caution level. Corresponding p-values are shown in brackets. For further info concerning the determinands, see [Robert C. Feenstra, Robert Inklaar, Marcel Timmer, 2013]).

Variable	$\phi Y_{it}/P_{it} \leq 6400$ precipitation ≤ 0.003 mm	$\phi Y_{it}/P_{it} \leq 6400$ precipitation > 0.003 mm	$\phi Y_{it}/P_{it} > 6400$ precipitation ≤ 0.0021 mm	$\phi Y_{it}/P_{it} > 6400$ precipitation > 0.0021 mm
Observations	486	468	468	432
Countries	27	26	26	24
$ln\left(\frac{Y_{it}}{P_{it}}\right)$	**-0.1180 (0.0189 *)**	**-0.3448 (0.0000 ***)**	**-0.1453 (0.0026 **)**	**-0.1586 (0.0001 ***)**
$ln\left(\frac{C_{it}}{P_{it}}\right)$	**0.4131 (0.0000 ***)**	0.5320 (0.0990 .)	**0.5164 (0.0003 ***)**	**0.4041 (0.0000 ***)**
$ln\left(\frac{L_{it}}{P_{it}}\right)$	-0.0048 (0.9776)	-0.0612 (0.7155)	**0.5900 (0.0026 **)**	**0.3149 (0.0296 *)**
$ln\left(\frac{H_{it}}{P_{it}}\right)$	1.8162 (0.2880)	9.3175 (0.0769 .)	-1.4556 (0.2242)	**2.7811 (0.1851 *)**
Precipitation	20.903 (0.0762 .)	4.0196 (0.8016)	**36.9380 (0.0173 *)**	10.9080 (0.1290)
Heat wave length	0.0003 (0.1764)	-0.0000 (0.8198)	0.0002 (0.6720)	**-0.0006 (0.0008 ***)**

Table 4..6: Panel GMM regression results for groups of countries partitioned by mean yearly per-person GDP and mean yearly HI. The numbers shown are estimates for coefficients explaining annual changes in logged, per-person output-side GDP, capital, labor and human capital measured in millions of 1995 USD as determined by the number of days in the longest heat wave of the year, whereas the longest heat wave is characterized by contiguous days in which the maximum daily HI exceeded the caution level. Corresponding p-values are shown in brackets. For further info concerning the determinands, see [Robert C. Feenstra, Robert Inklaar, Marcel Timmer, 2013]).

Variable	$\phi Y_{it}/P_{it} \leq 6400$ HI ≤ 70	$\phi Y_{it}/P_{it} \leq 6400$ HI > 70	$\phi Y_{it}/P_{it} > 6400$ HI ≤ 46	$\phi Y_{it}/P_{it} > 6400$ HI > 46
Observations	468	486	450	450
Countries	26	27	25	25
$ln\left(\frac{Y_{it}}{P_{it}}\right)$	**-0.1482** **(0.0218 *)**	**-0.2012** **(0.0083 **)**	**-0.0815** **(0.0227 *)**	**-0.2620** **(0.0 ***)**
$ln\left(\frac{C_{it}}{P_{it}}\right)$	**0.4093** **(0.0054 **)**	**0.4120** **(0.0 ***)**	**0.2855** **(0.0001 ***)**	**0.5437** **(0.0018 **)**
$ln\left(\frac{L_{it}}{P_{it}}\right)$	-0.0321 (0.8372)	-0.0075 (0.9549)	**1.0170** **(0.0 ***)**	0.1000 (0.4552)
$ln\left(\frac{H_{it}}{P_{it}}\right)$	0.5047 (0.7096)	**10.8713** **(0.0264 *)**	**-2.8922** **(0.0532 .)**	0.9122 (0.4598)
Precipitation	**23.7068** **(0.0280 *)**	2.2972 (0.9064)	**2.4018e+01** **(0.0066 **)**	10.9411 (0.2798)
Heat wave length	**0.0004** **(0.0943 .)**	-0.0001 (0.3502)	-0.0001 (0.5916)	0.0002 (0.2505)

Table 4..7: Panel GMM regression results for groups of countries partitioned by mean yearly per-person GDP and mean daily precipitation. The numbers shown are estimates for coefficients explaining annual changes in logged, per-person output-side GDP, capital, labor and human capital measured in millions of 1995 USD as determined by the number of days in the longest heat wave of the year, whereas the longest heat wave is characterized by contiguous days in which the maximum daily HI exceeded the caution level. Corresponding p-values are shown in brackets. For further info concerning the determinands, see [Robert C. Feenstra, Robert Inklaar, Marcel Timmer, 2013]).

Variable	$\phi Y_{it}/P_{it} \leq 6400$ precipitation ≤ 0.003 mm	$\phi Y_{it}/P_{it} \leq 6400$ precipitation > 0.003 mm	$\phi Y_{it}/P_{it} > 6400$ precipitation ≤ 0.0021 mm	$\phi Y_{it}/P_{it} > 6400$ precipitation > 0.0021 mm
Observations	486	468	468	432
Countries	27	26	26	24
$ln\left(\frac{Y_{it}}{P_{it}}\right)$	**-0.1182 (0.0174 *)**	**-0.3419 (0.0000 ***)**	**-0.1460 (0.0030 **)**	**-0.1711 (0.0001 ***)**
$ln\left(\frac{C_{it}}{P_{it}}\right)$	**0.4239 (0.0000 ***)**	0.3687 (0.2239)	**0.5078 (0.0004 ***)**	**0.3647 (0.0000 ***)**
$ln\left(\frac{L_{it}}{P_{it}}\right)$	-0.0144 (0.9378)	-0.0577 (0.7418)	**0.5960 (0.0030 **)**	**0.34814 (0.0250 *)**
$ln\left(\frac{H_{it}}{P_{it}}\right)$	1.7842 (0.3114)	**8.7969 (0.0875 .)**	-1.5608 (0.1379)	**2.9478 (0.0143 *)**
Precipitation	**25.5510 (0.0428 *)**	5.9859 (0.6904)	**36.9643 (0.0409 *)**	6.0881 (0.2667)
Heat wave length	0.0000 (0.0939)	0.0001 (0.7169)	**-0.0008 (0.0096 **)**	0.0001 (0.4247)

Chapter 5

Conclusions

Implications

Heat has a substantial impact on human life. This is not new knowledge, but the extent wich which heat affects human society is larger than previously believed.

As shown in chapter 2, not only temperatures, but also perceived temperatures for humans are rising. Across the globe, the probability of extreme heat events characterized as dangerous for humans has increased substantially. The changes in heat index, on a climatological level, have led to a shift in the heat index regime that can be expected in many countries. The effect of heat on people is intensifying.

Chapter 3 demonstrates some of this process' tangible consequences. In Europe as a whole, the number of hot days, their length and frequencies all display significant, positive relationships with mortality. Particularly the elderly are in danger of heat-related mortality. Surprisingly, economic attributes of regions interacted counterintuitively with heat, as more economically productive regions were affected more strongly than regions with less economic productivity. This is not purely an issue of acclimatization, as regions with high mean heat index tend to have stronger relationships between high heat index and mortality than typically cool regions.

These results are significant because they show that Europe in particular - and, we can infer, the world as a whole - will not automatically become less vulnerable to heat in the course of future climate change. Most areas of high economic activity have aging demographic structures. These populations are at particular risk for suffering increased mortality due to hot weather. Simultaneously, the findings indicate that higher economic productivity will not necessarily increase resilience toward heat. The results demonstrate that in many instances, regions with high economic activity were more vulnerable to heat-related mortality. Therefore, simple increases in economic productivity that are normally associated with economic development, accompanied by the usual higher access to amenities such as water, air conditioning, etc. will not be a panacea in times to come. Nor will acclimatization be of particular help. In the case of mortality, the best option seems to be to adapt and not to wait out the process until populations are better equipped to deal with these hazards by using purely technological solutions.

In chapter 4 this relationship is further analyzed, this time on a global scale. Having confirmed that heat leads to higher death rates, it is straightforward to infer that heat has negative effects on other human systems. The process driving climate change, and thus the increase of hot weather, is rooted in economic productivity, and thus the feedback loop from heat to economic productivity is of interest.

We see that heat affects economic growth negatively. The results are consistent with those presented in chapter 3: countries with high economic productivity have the highest costs in terms of economic growth when confronted with hot weather.

Thus we see that particularly economically developed populations with elderly populations - a portrait of the powerful nations of the twentieth century as they transition into the twenty first - are the most vulnerable to hot weather, both in terms of mortality and in terms of economic growth. Naturally, climate change is a multifacetted phenomenon and there are many other mechanisms with which climate change affects human well-being. In many areas, developing countries are the most vulnerable towards our changing climate. However, in this case it seems that one of the most direct and tangible consequences of carbon emissions - heat in the form of perceived temperature - has the strongest effects on those who have the largest hand in causing it.

Limitations

The limitations to this thesis can be taken in part from the theoretical difficulties in quantifying the topic, as well as from the thesis' implications.

As demonstrated in chapter 1, measuring both heat itself in interaction with the human body, as well as human well-being, the object of interest for the thesis, is fundamentally difficult. Not only is a body's reaction to heat heavily dependent on the environment, it is also dependent in large part on the subject in question and their behavior. Here I believe to have found the best feasible compromise for global and regional scale analyses. Nonetheless, as shown in chapter 2, chapter 3 and chapter 4, using heat index to quantify heat's effects on humans is not the end of the story. In this thesis I attempted a nuanced approach, which considered heat wave duration and frequency, as well as the general and possibly disjoint occurrence of hot days, separately. A better understanding of the mechanisms behind these three components of heat would allow for a more refined examination of their effects on humans.

The attempts I have made to measure human well-being are necessarily flawed due to the difficulties in measuring this in a meaningful way. Although health - which was investigated from a high-level perspective in the form of mortality - and economic prosperity - which was investigated using the somewhat dubious metric of gross domestic product - surely play roles in human well-being, they are by no means the only way to describe this complex entity. Here, also, the mantra was to use what was available. Although more meaningful ways of measuring human well-being have been suggested in the past, it will be a long time before these new metrics are available with the required granularity, on the correct spatial scale and in a long enogh time series in order to be used in studies such as these.

The criticisms with working with GDP and mortality as metrics for human well-being could well be applied to all other data used for this thesis. The dataset for global population distribution, GRUMP, has its weaknesses, as do the economic data in the Penn World Table and the mortality data in the Eurostat tables. Particularly in their case, however, these data were not chosen in spite of these disadvantages - these disadvantages become strengths under consideration of those that other datasets have. The state of econometric and demographic data - especially worldwide - is sadly neither complete nor high in quality. More and better data would have been a great asset to these investigations.

It is for this reason that this thesis is limited, not so much in its scope but in its granularity. Having demonstrated that heat does affect human well-being, particularly through mortality and economic growth, the data is unable to explain through what mechanisms this occurs. This leaves much room for improvement and refinement of the findings described here.

Not only the mechanisms at play, but also their applications, are areas which this thesis has not been able to investigate. For example, some groups of regions - particularly those with high economic productivity - show less resilience towards heat than othes. This is consistent across the areas of economic growth and health. The results demonstrate that this is not simply a matter of acclimatization - typically hot regions and countries do not necessarily respond more robustly to heat than typically cool regions. Other factors are at play which cannot be revealed by the data here, yet are worthy of investigation.

Outlook

This thesis has demonstrated that heat in the context of climate change is an important component in coupled human-environment systems. It has demonstrated that heat increases mortality and decreases economic growth heterogeneously on a regional and national basis throughout Europe and the world. It also has produced the first inter-decadal, gridded global dataset of perceived temperature.

Further studies should investigate the mechanisms with which heat affects human systems. We see that heat affects economically productive regions more strongly than those with low economic productivity. What causes this? What can vulnerable regions do to increase their resilience toward hot weather? Understanding the answer to this question could help preserve lives around the world, especially as our populations continue to become more elderly.

The question of economic growth also deserves more attention. Why are prosperous regions more strongly impacted by hot weather than others? Is it due to an across-the-board lacking adaptation to hot weather, or does the answer lie in the composition of these developed economies? A cross-sectoral analysis of the effects of heat on different industries would offer useful insight into these questions.

In the end, many of the questions raised by this thesis can best be answered using qualitative work. Case studies investigating robust and vulnerable regions would be a good starting point. This would allow us to highlight the precise reasons that some areas react better to hot weather than others. Another potential advantage would be the ability to provide information to policy makers concerning what they can do to protect the populations in their charge.

On the operational front, this knowledge would also be of use in issuing warnings and advising the population on properly dealing with heat. The current practice of using more or less arbitrary thresholds to issue official heat warnings is demonstrably ineffective, as we have seen that not all regions are affected in the same ways. Likewise, it is unlikely that the same strategies for mitigating hot weather will be applicable in all places. Understanding regions' vulnerabilities and adapting warnings accordingly could better public health. It could also lead to more long-term solutions to make economies more robust against heat.

This thesis has shown that heat in and of itself is a tangible factor in human well-being. The magnitude of its effects can be expected to increase rather than decrease in the next decades, as populations age and climate change takes its course. Much has been learned, but there is still large potential for further studies in order to apply the knowledge gained here. It is my hope that this thesis can serve as a stepping stone for further research in order to make populations more safe and economies more robust towards heat in the course of climate change.